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Editor-in-Chief

Boris S. Sokolov

Member of the Russian Academy of Sciences,
Counsellor of the Presidium of the Russian Academy of Sciences

Address for correspondence: Staromonetnyi per. 22, Moscow, 109180 Russia
Phones: 7 (095) 231-2164; Fax: 7 (095) 233-5590.

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Some Regularities in *Homo* Genus Evolution Inferred from the Cranium Sphericity Degree

E. A. Vangengeim*, M. A. Pevzner*, and A. P. Pestryakov**

** Geological Institute (GIN), Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 109017 Russia*
*** Institute of Ethnology and Anthropology, Russian Academy of Sciences, Leninskii pr. 32a, Moscow, 117334 Russia*

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Abstract—The time dependence of the cranium sphericity degree of fossil humans from 48 sites in Europe, Asia, Africa, and Australia was studied. This parameter was established to follow the areacotangent law throughout the Pleistocene. Chronological intervals for all considered sites were determined by biometric dating. The intervals either completely or partially overlap with the published chronological data.

Key words: *Homo, Pleistocene, evolution, cranium sphericity degree, biometric dating.*

INTRODUCTION

Using some Pliocene and Quaternary mammalian phyletic lineages as an example, we showed that certain morphological features illustrating the evolutionary trend follow a uniform law. The law is described by the areacotangent formula, i.e., by the inverse hyperbolic function when $X > 1$ (Pevzner and Vangengeim, 1994).

This work was aimed at revealing weather the law can be applied to human morphological evolution throughout the Quaternary.

MATERIALS AND METHODS

We took the cranium sphericity degree (CS) index (Pestryakov, 1991) as the morphological evolutionary parameter to be studied. It was calculated by using the formula

$$CS = (200 - DI + BI + HI) : 3,$$

where $DI = \frac{l}{b}\frac{l}{h} \times 100\%$ is the dolichoid index; $BI = \frac{b}{l}\frac{b}{h} \times 100\%$ is the brachyoid index; $HI = \frac{h}{l}\frac{h}{b} \times 100\%$ is the hypsioid index; and l, b, and h are the largest longitudinal, transverse, and height diameters of a cranium, i.e., its parameters nos. 1, 8, and 17, respectively, according to the standard craniologic Martin's list.

For the analysis, we used data on 66 skulls of Paleolithic humans from 48 sites: 1 from Australia, 12 from Asia, 5 from Africa, and 30 from Europe. The interperpendicular diameters of skulls necessary for the calculation of the CS index were taken from the well-known work of Alekseev (1978). Pestryakov measured the corresponding parameters of the Koobi Fora skull 3733 using its cast. The sex affinity of the studied skulls was ignored, as the preliminary research of this feature in the considered craniologic series showed the lack of a substantial difference between male and female skulls.

The age of sites was determined by stratigraphic and various physical methods (see table).

The CS indexes of the Paleolithic skulls were compared with those of modern humans calculated from 80 modern craniologic series (nonweighted) including over 5000 skulls. Unfortunately, the craniologic series used by Pestryakov in the above-mentioned publication represent only the population from the northern half of the Old World, namely, 40 series were taken from Europe and 40 others from eastern Asia. However, we emphasize that the obtained CS parameter is similar to that of most other modern cranioseries. Only the dominant population of the tropical zone in the Old World and relatively less numerous American Indians and Eskimos are characterized by a somewhat lesser magnitude of CS.

It should be noted that the material on the Paleolithic fossil humans, when used for the purpose at hand, has some obvious disadvantages.

First, skull series are generally missing in this case, and a great variability of the chosen parameter, as exemplified by modern skulls, prevents us from using the statistical method for the determination of mean CS values.

Second, strongly fragmented fossil skulls frequently make the reliability of reconstructions and, consequently, the accuracy of measurements doubtful. Skulls with reliable measurements of all three diameters were available only in 21 of 48 considered sites (see table).

Third, most sites are located in caves, rock shelters, and grottos, and this hampers and often eliminates the exact correlation of bone beds with the Quaternary stratigraphic scale. This is evident from substantial discordances between the age data for sites suggested by

Values of cranium sphericity degree (CS) and age determinations of skulls

No.	Site	Skull no. and sex	Validity of values *l*, *b*, and *h*	CS	Dating after various authors		Probable time interval from biometric data (ka)
					stratigraphic	ka	
1	2	3	4	5	6	7	8
1	Le Placard (France), rock shelter	♀	+++	81.3	Würm 3/4–Neolithic (2)		0–14
2	Cap Blanc (France), rock shelter	♀	+??	80.2	Early Würm 4 (2), late Würm (22)	A_3: 12000–17000 (22)	0–19.1
3	Solutré (France), open-air site	I ♀	???	79.8	Modern prehistorical (2)		
		II ♀	++?	79.9			0–20.6
4	Döbritz (Germany), cave	♂	+++	79.4	Late Würm (2), beginning of the Würm 4 (4)	? 21 (4)	0–22.8
5	Zhoukoudian Upper Cave (China)	101 ♀	+++	73.1	Late Pleistocene (3)	C^{14}: > 10.5 < 18.3 (5)	1.2–27.2
		102 ♀	+?+	78.0			(according to 102, 103)
		103 ♀	+++	79.5			
6	Chancelade (France), cave	♂	+??	78.7	Würm 4 (2), late Würm (22)	≈15 (4) A_3: 12000–17000 (22)	1.4–27.2
7	Roc de Sers (France), rock shelter	♂	++?	78.5	Würm 3/4 (2)		1.9–30
8	Tuntienyen (Liujiang) (China), cave	♂	+++	78.3	Late Pleistocene (3), terminal Pleistocene-Holocene (6), ? early late Pleistocene (22)		2.6–30
9	Grimaldi, Barma Grande (Italy), grotto	♂	+??	78.2	Late Pleistocene (2), late Würm (22)	12 (4)	2.9–31
10	Brno, ul. Sushinova (Czech Republic), open-air site	III ♀	+??	77.9	Würm 2 or 3 (2), Würm (22)	≈26 (4) ≈26, 32 Brno 2 (4) ≈14 (ul. Koneva) (8)	3.9–31
11	San Teodore (Italy), cave	I ♂	+++	77.0	Late Pleistocene,		3.8–33.7
		II ♂	+++	79.4	late Paleolithic,		$13.5 \pm \frac{3.0}{2.5}$
		III ♂	++?	77.6	Romanelli facies (2)		
		V ♂	???	77.7			
12	Keilor (Australia), terrace alluvium	♂	+++	77.5		A_1: ^{14}C: 12.9 ± 0.12 (3) ^{14}C: 13.0 ± 0.1 (5) A_2: ≈ 15 (22)	5.4–36.8
13	Sungir' (Russia), open-air site	♂	++?	77.5	Middle Würm (22), beginning of the Würm 3 (9)	A_2 ^{14}C: 24.4 ± 0.4 (9) 25.0 ± 0.2 (11)	5.4–36.8
14	Saint Germain La Rivière (France), rock shelter	♀	+++	77.3	Würm 4 (2)		6.1–39.4
15	Oberkassel (Germany), quarry	♂	+?+	77.3	Würm 4 (2), late Würm (22)	A_3: 12–17 (22) ≈15 (7)	6.1–39.4
16	Engis I (Belgium), cave	♂	+++	76.8	Würm (2, 22), Würm 3 (4)	? 25 (4) ≈21 (E. 2) (7) A_3: 35–70	8.6–43.7
17	Kostenki XIV (Russia), open-air site	♂	+++	76.7	Late Würm (2)	^{14}C: > 26.3 ± 0.7 28.1 ± 0.7 (10) 28–30 (oral communication of N.D. Praslov)	9–45

Table. (Contd.)

1	2	3		4	5	6	7	8
18	Předmosti (Czech Republic), open-air site	III	♂	+??	73.3	Würm 2 or 2/3 (2),	A_3: 26 (2, 4)	7.5–42.1
		IX	♂	+++	76.1	Würm (22)	≈27 (8)	
		IV	♀	+++	77.9		≈26.5 (22)	
19	Wadjak (Indonesia), travertines		♂	+++	76.2	Late Pleistocene or early Holocene (3)		11.7–51.9
20	Le Moustier (France), rock shelter (J and H beds)		♂	++?	76.0	Würm 2 (2), Würm (22)	A_3: 35–70 (22) 40–56 (4) 40 (6) A_2 TL (15): bed K 42.6 ± 3.2 bed J 40.3 ± 2.6 bed I 40.9 ± 0.5 bed H 42.5 ± 2; 46.3 ± 2 bed G: 55.8; 50.3 ± 5.5	13.2–53.9
21	Jebel Qafzeh (Israel), grotto (Bed L)	VI	♂	++?	75.9	Early Würm interstade (22); end of the last interpluvial (3). Würm 1 + 1/2; first half of the Würm (15)	TL: ≈ 92 (6) A_1A_k: 40/46 (15); bed. XXII (below the skull) A_k: 68/78; TL: 92 ± 5 (15); A_4: ≈ 60 (22); ESR: 98 (15) 100 ± 0.1 (Eu) (16) 120 ± 0.08 (Lu)	13.7–55.6
22	La Ferrassie (France), rock shelter	I	♂	+++	75.5	Würm 2? (2). Würm 1 or Würm 2 (15). Würm (22)	^{14}C: >35 (15) A_3: 68–75 (3 and most part of Stage 4 from $\delta^{18}O$) (15) 47.5 (7) 72 (6)	16.5–62.1
23	Kostenki II (Russia), open-air site		♂	???	75.4	Late Würm (2)	16.1 (11) A_2 ^{14}C: 11 ± 0.2 (2) 18 (oral communication of Praslov)	17.8–62.1
24	Skhul B (Israel), cave	V	?♂	++?	75.3	Riss-Würm;	≈40 (4, 17)	18.5–64.3
		IX	♂	???	68.7	Würm interstade (3), beginning of the Würm (6), middle Würm (22)	ESR and TL: ≈ 100 (7)	(according to V)
		IV	♂	???	71.6	Beginning of the Würm (6) Middle Würm (22)	ESR: 81 ± 15 (Eu) 101 ± 12 (Lu) (16) A_1A_k: 39/40 (15) A_3: ≈ 40 (according to technol. chronol.) (15)	
25	Grimaldi. Grotte des Enfants (Italy)	(cromagnon-man)	♂	???	76.6	Late Pleistocene (2), Würm 3 (4),	≈30 (4) 20–21 (12)	17.9–63.9
		("negroid")	♀	++?	74.1	late Würm (22)		
26	Mladeč (Czech Republic), cave	I	♂	+++	75.2	Würm 1/2 (2) Würm 2/3 (4) Würm (22)	≈35 (4, 7)	19.1–66.6

Table. (Contd.)

1	2	3		4	5	6	7	8
27	Dolni Vestonice (Czech Republic), open-air site	III	♀	+++	75.2	Paudorf (Würm 2/3) (2), Würm (22)	A_3 ^{14}C: 29 ± 0.2 (2) 25.82 (7) ≈26 (4) ^{14}C: 31.7 ± 1 28.229 ± 0.37 26.430 ± 0.19 27.660 ± 0.8 } (13)	19.1–66.6
28	Tabun (Israel), cave	I	♀	++?	75.0	Terminal Riss-Würm (3); Riss-Würm; beginning of the Würm 1; terminal Würm 1; Würm 1–2 (15); bed B–middle Würm (22)	A_2 ^{14}C: bed. C 40.9 ± 1 bed. B 39.7 ± 0.9 overlying bed 29.45–36 A_k: bed. C 51/53 (3) A_k: bed. C 63/65 64–32 (3rd st. ^{18}O) (15) ESR: bed. B 100 (Lu) bed. C 120 (Lu) (16)	21.2–69.1
29	Shanidar (Iraq), cave	I	♂	+++	74.8	Late Pleistocene (3), Würm 1/2 (15), early Würm (22)	A_2 ^{14}C: 46.9 ± 1.5 (3) 50.6 ± 3 (9) >45 (4) A_4: >60 (22)	22.8–74.5
30	Koobi Fora (Kenya), erosional slope	3733	♀	+++	74.8	Top of the Koobi Fora Formation (19)	1.6–1.8 Ma (6)	22.8–74.5
31	Urtiaga B (Spain), cave		♂	+++	74.6	Würm 3 (2)	^{14}C: bed. F 17.05 ± 0.14 (14)	25.3–77.5
32	Cro-Magnon (France), rock shelter		♂	++?	74.6	Würm 3 (2), Würm (22)	≈32 (6) ≈30 (7) A_4: 20–30 (22)	25.3–77.5
33	Fish Hoek (South Africa), rock shelter		♂	+++	74.5	Pleistocene (1), early Holocene (22)	A_2: >35.6 36 ± 2.4 (1)	26.2–80.8
34	Gibraltar, Forbes Quarry	I	♀	+??	74.2	Riss-Würm or Würm 1 (6), Würm (2)	A_3: 45–70 (7) ≈75 (7)	30–87.3
35	La Chapelle-aux-Saints (France), cave		♂	+++	73.6	Würm 2 (2), Würm (22)	A_3A_k: 60/64 (15) ≈60 (6); 47.5 (7); 40 (4) 35–45 (22)	38.1–106.9
36	Saccopastore (Italy), alluvium		♀	+++	73.6	Riss-Würm (2), Riss 3 (at the Riss-Würm boundary) (4), late Eemian (22)	A_3: ≈ 60 (2) 90–130 (6) 60 or 120 (4) >60 (22)	38.1–106.9
37	Fontéchevade (France), cave		♂	???	73.4	Riss-Würm (2), Eemian (22)	130–190 (6) 100 (4) A_4: 70 – ? 150 (22)	42.1–111.6
38	Sangiran (Indonesia), *ex situ*	P II	♀	++?	73.2	Kabu Formation,	500–800 (6)	46.8–116.6
		P VIII	♂	+?+	77.3	Trinil fauna (3, 6, 22)	≈500 (22)	6.1–39.4
39	Monte Circeo (Italy), cave	I	♂	++?	73.1	Terminal Würm 1, early Würm 2 (2), Würm (4, 22)	A_3 ^{14}C: 58.5 ± 0.8 (9) ≈65 (4) A_3: 35–70 (22)	48.5–120.7
40	Amud (Israel), cave	I	♂	++?	72.8	Würm 1 (4) Würm (22)	A_2 FT.: 28 ± 35% Ionium 27 ± 5 (3) ?75 (4); 75–80 (17)	55.6–133.1

Table. (Contd.)

1	2	3	4	5	6	7	8
41	Jebel Irhoud (Morocco), cave	II ♂ I ♂	+++ +++	72.4 73.0	Early late Pleistocene (6), Soltanian (=Würm) (22)	A_2 ^{14}C: >30 (1) 130 (6); ≈100 (18) ESR: 130–190 (21) ESR: 105–190 (16)	57.7–138.3
42	Ngandong (Indonesia), alluvium of 20-m-high terrace	VI ♀ I ♀ IX ♀ X ♀ XI ♂ V ♂	++? ++? ++? ++? +++ ++?	74.1 72.8 72.7 72.1 71.6 66.9	Late Pleistocene (3), Würm (9), late middle Pleistocene (6), late Pleistocene (22)	200–500 (6) Th/U: ≤75–100 (20)	58.5–142.1 (without V) $88 \pm \overset{16.6}{13.0}$
43	Zhoukoudian I (China), cave	XI ♂	++?	71.0	Mindel 2; Mindel-Riss (3), Mindel 2 (22)	$A_{2/3}$: 210–>500 (3) 240–500 (6) 370 (9) FT.: bed. 10 462 ± 0.45 TL.: upper culture bed. 290 lower culture bed. 610 Th/U: bed. 8, 9 $420 \pm \overset{>180}{100}$ bed. 1–3: $230 \pm \overset{0.3}{0.2}$ $256 \pm \overset{0.62}{0.4}$ >200 < 600 (23)	133–289.2
44	Petralona (Greece), cave	♂	+++	70.8	Late Pleistocene (3), Würm (22)	300–500 (6) >200 < 730 (6)	152.3–315.2
45	Eyasi (Tanzania), lacustrine deposits	♂	???	70.4	Late Pleistocene (1), terminal middle Pleistocene (6), Gamblian pluvial (= Würm) (22)	>130 (6); ≈200 (18) A_1A_k: 34 (1) <60 (22)	200.3–403.7
46	Broken Hill (Zambia), cave	♂	???	70.4	Late Pleistocene (1), terminal middle Pleistocene (6), late Pleistocene (22)	A_1A_k:110 (1) A_3 ^{14}C: 35–45 (according to culture) (1) >130 (6) 220–230 (18) A_3: ≈40 (22)	200.3–403.7
47	Steinheim (Germany), alluvium	♀	++?	70.1	Riss 1/2 or Mindel-Riss (2), late Hoxnian (= Mindel-Riss) (22)	250–400 (6) A_4: ≈200 (22)	256.1–488
48	Trinil (Indonesia), alluvium	P I ♀	???	69.8	Kabu Formation, Trinil fauna (3, 22)	500–800 (6) ≈500 (22)	335–619

Note: Dating methods: TL—thermoluminescence; FT—fission-track; A_k—amino acid epimerization; ESR—electron spin resonance. Age of an object in years was determined from A_1—direct age determination of the specimen itself; A_2—direct age determination of enclosing deposits or included organic remains (animal bones, charcoal, wood); A_3—correlation of the source bed with sediments of known age; A_4— theoretical constructions.

Data are cited from the following works: (1) Oakley *et al.*, 1977; (2) Oakley *et al.*, 1971; (3) Oakley *et al.*, 1975; (4) Clark and Lindly, 1989; (5) Brown, 1993; (6) Klein, 1989; (7) Smith *et al.*, 1989; (8) Svoboda, 1990; (9) Ivanova, 1965; (10) Lazukov *et al.*, 1981; (11) Velichko and Kurenkova, 1990; (12) Mussi, 1990; (13) Otte, 1990; (14) Straus, 1990; (15) Smirnov, 1991; (16) Schwarcz and Grün, 1993; (17) Rightmire, 1989; (18) Clark, 1989; (19) Leakey and Walker, 1976; (20) Jones, 1993; (21) Smith, 1993; (22) Oakley, 1966; (23) Watanabe and Kadar, 1985.

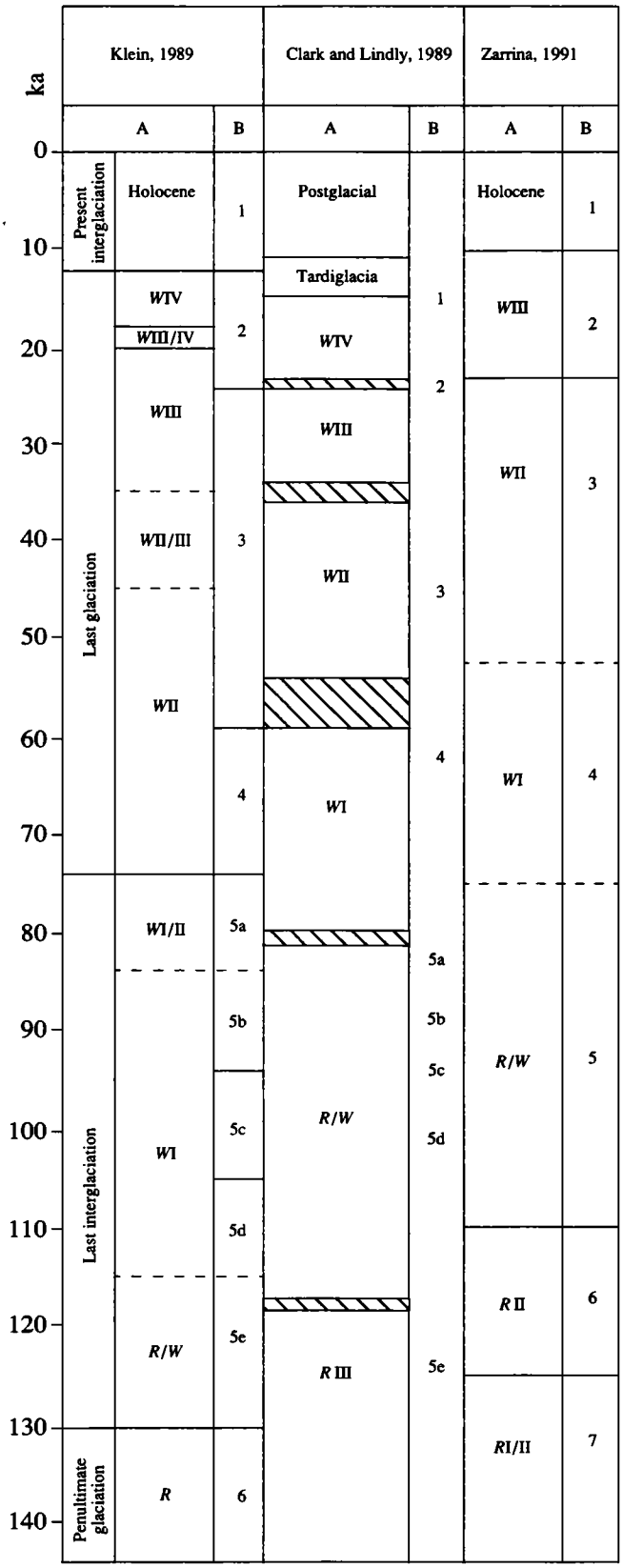

Fig. 1. Subdivision of the late Pleistocene in Europe after various authors. A – glacial stage chronology; B – oxygen-isotope stages. Intervals of feasible position of boundaries are crosshatched.

different authors. For instance, the site at the Saccopastore Cave was dated back to the terminal Riss (Clark and Lindly, 1989) or to the second half of the Riss-Würm (Oakley, 1966). Disagreements in data are typical of sites of other taphonomic types as well. For example, the alluvial Ngandong site was dated to be in the intervals from 75 to 100 ka (Jones, 1989) and from 200 to 500 ka (Klein, 1989).

Fourth, various stratigraphic scales, among them that of the late Pleistocene, include a different number of subdivisions, and the age of their boundaries is variously estimated (Fig. 1). Thus, even the sites assigned to a single stratigraphic subdivision can have different absolute ages.

Fifth, different physical methods of age determination of the same site often produce inconsistent results (see table).

The time interval beyond the possibilities of radiocarbon dating, i.e., older than 40 ka, is characterized by a particularly pronounced uncertainty in the absolute age determination of sites. However, despite the disadvantages mentioned above, even the preliminary analysis of the data shows that the time dependence of the CS index can be described by the areacotangent formula.

We used three reference points on the areacotangent curve to determine scales along the X and Y axes.

(I) Skulls of modern humans. The year 1900, i.e., 0.1 ka ago, is taken as the mean starting point. The CS index (82.05 ± 0.20) and σ (± 1.83) values resulted from averaging the data on 80 craniologic series.

(II) Skulls of the late upper Paleolithic humans, about 10–20 ka old. They are from the following sites: Kostenki II, San Teodore (4 skulls), Wadjak, Keilor, Oberkassel, Saint Germain La Riviere, Chancelade, Döbritz, Cap Blanc, Roc de Sers, Barma Grande, Urtiaga B, and Tuntienyen. Their mean age is 15 ka; the mean CS index is 77.71 ± 0.36; $\sigma = \pm 1.45$; and $n = 16$.

(III) Skulls of the early upper Paleolithic humans, about 25–35 ka old. They are from the Engis, Dolni Vestonice, Grimaldi (2 skulls), Kostenki IV, Cro-Magnon, Mladeč, Fish Hoek, and Sungir' sites. Their mean age is 30 ka, CS = 75.63 ± 0.41, $\sigma = \pm 1.22$, and $n = 9$.

To judge to what degree the empirical data agree with the theoretical concept, we should know the mean square deviation from the mean value of σ. We have no statistical characteristics for fossil humans. The σ value of a modern human constitutes 13.6% of the distance from the X axis to the mean CS value on the areacotangent curve. Such a relationship is assumed to be constant in time and true for all fossil findings. With this assumption, we calculated the mean square deviation σ for the entire studied period.

DISCUSSION

Figure 2 shows the position of skulls from considered sites relative to the areacotangent curve.

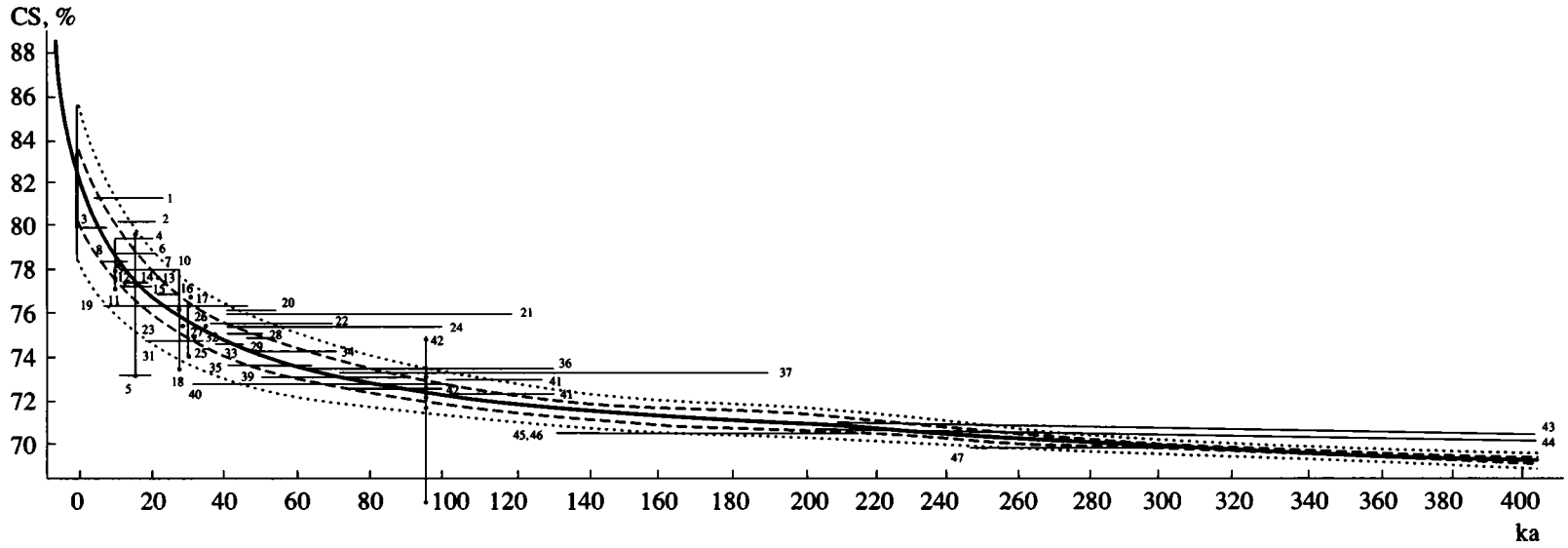

Fig. 2. Time-dependent changes of the cranium sphericity degree (CS) of skulls of fossil humans approximated by the areacotangent curve (solid line); dashed and dotted lines outline values of mean square deviations 1σ and 2σ, correspondingly; horizontal lines are the intervals within which the age of sites is estimated by various authors and methods; vertical lines connect CS values of skulls from the same site; the extreme left vertical line is the range of CS variability of modern humans (the thick part corresponds to 1σ, the thin part, to 2σ); 1–47—numbers of sites (see table).

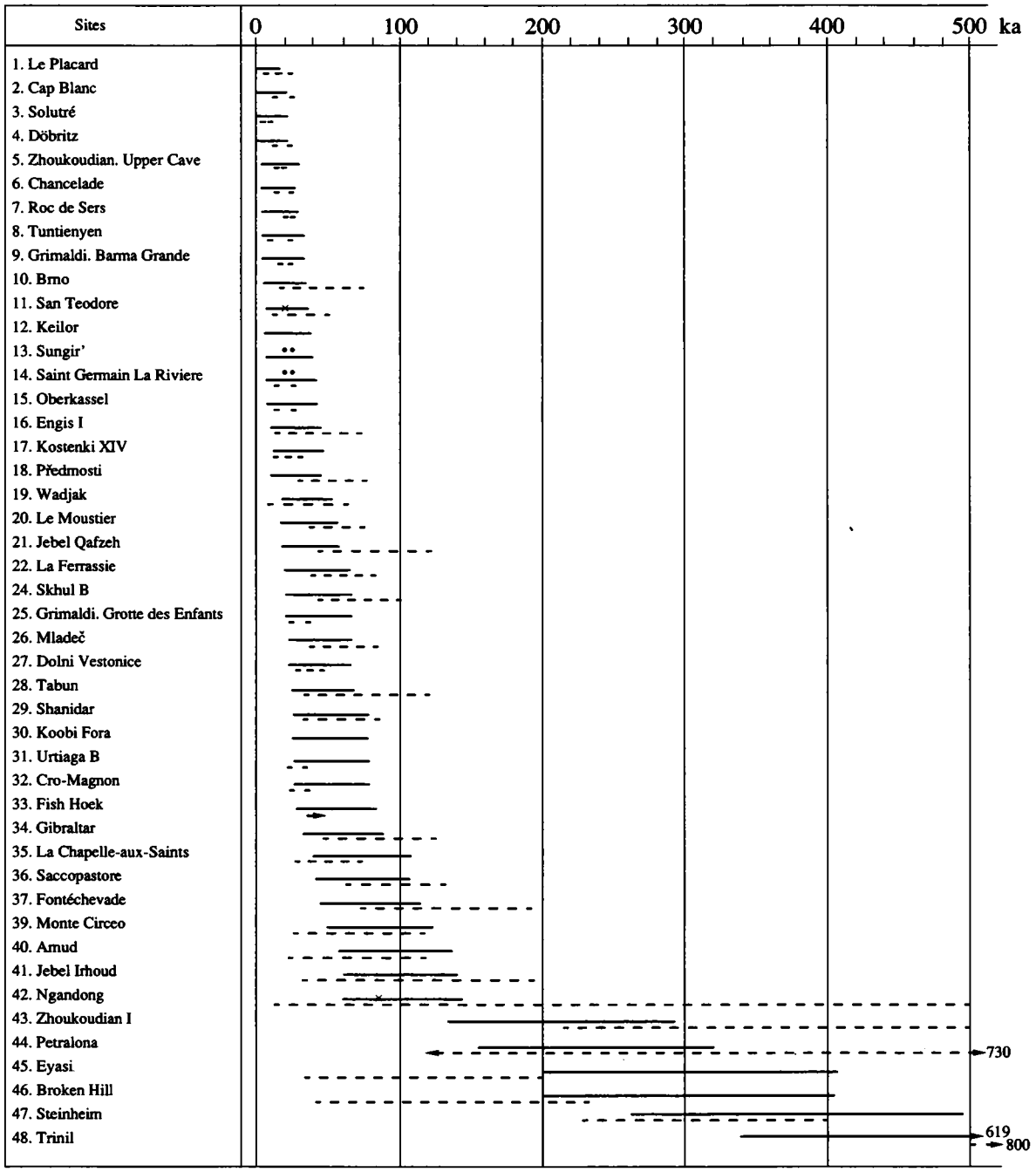

Fig. 3. Time intervals of sites with fossil human remains. The solid line is the time interval from biometric data; the dashed line—from radiometric, stratigraphic, and other data. Dots are single ^{14}C datings; × is the mean age evaluated by the biometric method.

As evident from the figure, the great majority of points lies close to the areacotangent curve within the interval from 1σ to 2σ. Therefore, we can conclude that the change in the skull sphericity degree of *Homo* representatives follows the areacotangent law. CS values of several skulls are beyond the interval limited by 2σ. Among these are the following samples: skull 101 from the Zhoukoudian Upper Cave (5), though two other skulls from this site fall within 2σ limits; skull III from Předmosti (18), two others are again within 2σ limits; skull V from Ngandong (42), which has a CS value of 66.9, which is less than the theoretically calculated minimum for the genus *Homo* (68.61); the remaining five skulls of the site are within 2σ limits.[1] The skulls of Javan pithecanthropes from Sangiran (P II and P VIII)

[1] Numerals in parentheses indicate the site numbers in the table and in Figs. 2 and 3.

and Trinil (P I) and skull 3733 from the Koobi Fora site are not shown in Fig. 2, because their presumable age is outside the figure boundaries. The skulls P II, P VIII, and 3733 plot substantially above the areacotangent curve beyond the of 2σ limits. Such a scatter could result either from improper skull reconstruction, or from the incorrect age determination of these sites.

BIOMETRIC DATING METHOD

As indicated earlier (Pevzner and Vangengeim, 1994), the time-dependent changes in a morphological parameter of different mammalian groups follow the areacotangent law and can be used for the biometric dating of localities. The mean value of the evolutionary morphological parameter (EMP) is used for the age determination of sites. If a great deal of EMP measurements is available for a certain site, then its age can be determined with a high accuracy.

The statistical data for determination of the mean CS value and its variability, which are necessary to establish an error in the calculated age of a site, are missing for most localities with human remains. A site cannot be dated by using the CS value of a single skull, as this value is not necessarily close to the average and can be at any place in the variability range. Nevertheless, we attempted to detect the most likely chronological intervals of the considered sites by the biometric method. For this purpose, we calculated a theoretically feasible σ value (see above) for the CS index of every skull. Chronological limits of sites were calculated from the CS value $\pm 2\sigma$ according to the formula $T = 59.62\frac{e^{0.198CS} : 795000 + 1}{e^{0.198CS} : 795000 - 1} - 68.492$ ka. It should be stressed once again that, though a certain CS index appears as a mean value of the parameter, it does not determine the average age of most sites. Two exceptions are localities with several skulls, namely, Ngandong with five and San Teodore with four skulls. Their average ages are $88.1\ ^{+16.6}_{-13.0}$ ka and $13.5\ ^{+3.0}_{-2.5}$ ka, correspondingly. The available biometric dating of the Ngandong site agrees well with the Th/U age of ≤75–100 ka (Jones, 1989) and coincides with the geologic records. The locality is in the sediments of the 20-m-high terrace of the Solo River assigned to the late Pleistocene (Von Koenigswald, 1939; Watanabe and Kadar, 1985). This age determination of the Ngandong site contradicts the dating of 0.2–0.5 Ma (Klein, 1989).

The San Teodore site yields tools assigned to the late Paleolithic Romanelli facies. The ^{14}C datings ranging from 9790 ± 80 to 11930 ± 520 years are available for the Romanelli Grotto with the same cultural remains (Oakley *et al.*, 1971). Thus our age determination of $13.5\ ^{+3.0}_{-2.5}$ ka agrees well with these data.

All time intervals determined by the biometric method for the considered sites overlap to some extent with the data on their age measured by other methods (Fig. 3), excluding skulls P II, P VIII, and 3733.

Let us discuss these exceptions.

Age intervals calculated by the biometric method for skulls P II (46.8–116.6 ka) and P VIII (6.1–30.4 ka) differ considerably from those proposed by other authors (500–800 ka). It should be noted that the definite geologic position of all skulls from the Sangiran site is unknown. The location of findings is known with some degree of certainty, but their position in the section is completely unknown (Watanabe and Kadar, 1985). Therefore, the data for the evaluation of their age are missing. On the other hand, the validity of the biometric age of skulls P II and P VIII depends on the reliability of their reconstruction. Since all diameters of both skulls have not yet been measured with assurance, we cannot consider the calculated age interval as quite reliable.

Though our age determination of skull P I from the Trinil site overlaps to some extent with the datings proposed by other researchers, it should be considered with caution, because the validity of the reconstruction of this skull is doubtful: all three of its diameters were reported with a question mark.

The presently accepted age of skull 3733, referred to *Homo erectus*, is 1.6–1.8 Ma. Its biometric age ranges from 22.8 to 74.5 ka.

According to Leakey and Walker (1976), the skull was found *in situ* on an erosional slope in sediments of the upper member of the Koobi Fora Formation between the KBS tuff and Koobi Fora-BBS tuff complex. The section in the site of the finding was not described. The K–Ar data for the KBS tuff in other regions are 2.61 (Fitch and Miller, 1976) and 1.89 Ma (Klein, 1989). The Koobi Fora and BBS tuffs were dated back to 1.56–1.57 Ma (Brock and Isaac, 1976). Findlater (1976) noted that in the Koobi Fora region the correlation of tuffs with those from other Lake Rudolf regions is reliable only for the lower part of the Koobi Fora Formation including the KBS tuff. As for the younger tuffs, they have no continuous distribution or specific visual or petrographic peculiarities that could help to distinguish them. The sediments have been strongly disturbed by tectonics and have numerous erosional gaps. All these facts severely hamper the correlation of both tuff units and intervening sediments.

This geologic situation casts some doubt on the validity of the assignment of skull 3733 to the upper member of the Koobi Fora Formation.

Some morphological peculiarities of the skull suggest its relatively young age. In addition to a large CS value (74.8), it differs from the classical East Asian *H. erectus* by a lesser thickness of the cranium bones and by the thinner, though also strongly pronounced, supraorbital torus. The African skull is of a more *sapiens* type than the classical *H. erectus* (Klein, 1989).

CONCLUSION

The proposed study allows the following conclusions to be made:

(1) The cranuim sphericity degree (CS) is one of the most distinct morphological parameters reflecting the evolutionary trend of the genus *Homo*.

(2) The time-dependent changes of the CS value can be approximated by the areacotangent curve.

(3) Since the CS value gradually increases up the time scale, without marked leaps, this parameter cannot be used for placing distinct morphological boundaries between certain species of the genus *Homo*.

(4) The biometric method allowed the determination of chronological intervals for all considered sites. The intervals are either completely or partially consistent with the published chronological data.

A probable mean age was determined for the San Teodore and Ngandong sites.

(5) The analysis of geologic records and morphological characteristics of skull 3733 from the Koobi Fora site casts some doubt upon its assignment to the upper member of the Koobi Fora Formation.

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REFERENCES

Alekseev, V.P., *Paleoantropologiya Zemnogo shara i formirovanie chelovecheskikh ras* (Paleoanthropology of the Earth's Globe and Formation of Human Races), Moscow: Nauka, 1978.

Brock, A. and Isaac, G.L., Reversal Stratigraphy and Its Application at East Rudolf, *Earliest Man and Environments in the Lake Rudolf Basin,* Coppens, Y. *et al.*, Eds., Chicago: University of Chicago, 1976, pp. 148–162.

Brown, P., Recent Human Evolution in East Asia and Australasia, *The Origin of Modern Humans and the Impact of Chronometric Dating,* Aitken, M.J., Stringer, C.B., and Mellars, P.A., Eds., Princeton: Princeton Univercity, 1993, pp. 217–233.

Catalogue of Fossil Hominids. Part II: Europe, Oakley, K.P., Campbell, B.G., and Molleson T.J., Eds., London: Trustes British Mus. (Nat. History), 1971.

Catalogue of Fossil Hominids. Part III: America, Asia, Australia, Oakley, K.P., Campbell, B.G., and Molleson T.J., Eds., London: Trustes British Mus. (Nat. History), 1975.

Catalogue of Fossil Hominids. Part I: Africa, Oakley, K.P., Campbell, B.G., and Molleson T.J., Eds., London: Trustes British Mus. (Nat. History), 1977.

Clark, J.D., The Origins and Spread of Modern Humans: A Broad Perspective on the African Evidence, *The Human Revolution. Behavioural and Biological Perspectives on the Origins of Modern Humans*, Mellars, P. and Stringer, Ch., Eds., Princeton: Princeton Univ., 1989, pp. 565–588.

Clark, G.A. and Lindly, M., The Case for Continuity: Observations on the Biocultural Transition in Europe and Western Asia, *The Human Revolution. Behavioural and Biological Perspectives on the Origins of Modern Humans*, Mellars, P. and Stringer, Ch., Eds., Princeton: Princeton Univ., 1989, pp. 626–676.

Findlater, I.C., Tuffs and the Recognition of Isochronous Mapping Units in the Rudolf Succession, *Earliest Man and Environments in the Lake Rudolf Basin,* Coppens, Y. *et al.*, Eds., Chicago: University of Chicago, 1976, pp. 94–104.

Fitch, F.J. and Miller, J.A., Conventional Potassium-Argon and Argon-40/Argon-39 Dating of Volcanic Rocks from East Rudolf, *Earliest Man and Environments in the Lake Rudolf Basin,* Coppens, Y. *et al.*, Eds., Chicago: University of Chicago, 1976, pp. 123–147.

Ivanova, I.K., *Geologicheskii vozrast iskopaemogo cheloveka* (Geological Age of Fossil Man), Moscow: Nauka, 1965.

Jones, R., East of Wallace's Line: Issues and Problems in the Colonisation of the Australian Continent, *The Human Revolution. Behavioural and Biological Perspectives on the Origins of Modern Humans, Mellars,* P. and Stringer, Ch., Eds., Princeton: Princeton Univ., 1989, pp. 743–782.

Klein, R.G., *The Human Career. Human Biological and Cultural Origins,* Chicago: University of Chicago, 1989.

Lazukov, G.I., Gvozdover, M.D., Roginskii, Ya.Ya., *et al.*, *Priroda i drevnii chelovek* (Nature and Ancient Man), Moscow: Mysl', 1981.

Leakey, R.E.F. and Walker, A.C., Australopithecus, *Homo erectus* and the Single Species Hypothesis, *Nature,* 1976, vol. 261, no. 5561, pp. 572–574.

Mussi, M., Continuity and Change in Italy at the Last Glacial Maximum, *The World at 18000 BP, Vol. 1: High Latitudes*, Soffer, O. and Gamble C., Eds., London. Unwin Hyman, 1990, pp. 126–147.

Oakley, K.P., *Frameworks for Dating Fossil Man*, London: Weidenfeld and Nicolson, 1966.

Otte, M., The Northwestern European Plain around 18 000 BP, *The world at 18000 BP, Vol. 1: High Latitudes,* Soffer, O. and Gamble C., Eds., London. Unwin Hyman, 1990, pp. 54–68.

Pestryakov, A.P., The Chronological Variability of the Cranium Total Size and Form as an Indicator of the Uniform Morphologic Evolution of Humans, *Races and Racism: History and the Present Time*, Natoburg, E.L. and Zolotareva, I.M., Eds., Moscow: Nauka, 1991, pp. 29–59.

Pevzner, M.A. and Vangengeim, E.A., Some General Features of Mammalian Evolution, *Stratigr. Geol. Korrelyatsiya,* 1994, vol. 2, no. 6, pp. 3–9.

Quternary Geology of the Hominid Fossil-bearing Formation in Java, Rep. Indonesia-Japan Joint Res. Project CTA-41, 1976–1979, Watanabe, N. and Kadar, D., Eds., *Spec. Publ.Geol. Res. Dev. Centre, Bandung,* 1985, no. 4.

Rightmire, G.Ph., Middle Stone Age Humans from Eastern and Southern Africa, *The Human Revolution. Behavioural and Biological Perspectives on the Origins of Modern Humans,* Mellars, P. and Stringer, Ch., Eds., Princeton: Princeton Univ., 1989, pp. 109–122.

Schwarz, H.P. and Grün R., Electron Spin Resonance (ESR) Dating of the Origin of Modern Man, *The Origin of Modern Humans and the Impact of Chronometric Dating,* Aitken, M.J., Stringer, C.B., and Mellars, P.G., Eds., Princeton: Princeton Univercity, 1993, pp. 40–48.

Smirnov, Yu.A., *Must'erskie pogrebeniya Evrazii* (Mousterian Burials of Eurasia), Moscow: Nauka, 1991.

Smith, F.H., Models and Realities in Modern Human Origins: The African Fossil Evidence, *The Origin of Modern Humans and the Impact of Chronometric Dating*, Aitken, M.J.,

Stringer, C.B., and Mellars, P.G., Eds., Princeton: Princeton Univercity, 1993, pp. 234–248.

Smith, F.H., Simek, J.F., and Harrill, M.S., Geographic Variation in Supraorbital Torus Reduction during the Later Pleistocene (c. 80 000–15 000 BP), *The Human Revolution. Behavioural and Biological Perspectives on the Origins of Modern Humans,* Mellars, P. and Stringer, Ch., Eds., Princeton: Princeton Univ., 1989, pp. 172–193.

Straus, L.G., The Last Glacial Maximum in Cantabrian Spain: The Solutrean, *The World at 18000 BP, Vol. 1: High Latitudes,* Soffer, O. and Gamble C., Eds., London. Unwin Hyman, 1990, pp. 89–108.

Svoboda, J., Moravia during the Upper Pleniglacial, *The World at 18000 BP, Vol. 1: High Latitudes,* Soffer, O. and Gamble C., Eds., London. Unwin Hyman, 1990, pp. 193–200.

Velichko, A.A. and Kurenkova, E.I., Environmental Conditions and Hhuman Occupation of Northern Eurasia during the Late Valdai, *The World at 18000 BP, Vol. 1. High Latitudes,* Soffer, O. and Gamble C., Eds., London. Unwin Hyman, 1990, pp. 255–265.

Von Koenigswald, G.H.R., Das Pleistocan Yavas, *Quarter.,* 1939, no. 2, pp. 28–53.

Zarrina, E.P., *Chetvertichnye otlozheniya severo-zapadnykh i tsentral'nykh raionov evropeiskoi chasti SSSR* (Quaternary Deposits in the Northwestern and Central Regions of the European Part of the USSR), Leningrad: Nedra, 1991.

Stratigraphy and Geological Correlation, Vol. 5, No. 6, 1997, pp. 536–547. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 5, No. 6, 1997, pp. 14–26.
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Local, Regional, and Correlation Schemes for the Precambrian of Karelia and Kola Peninsula: The Historical-Methodological Analysis

V. Z. Negrutsa

Geological Institute, Kola Scientific Center, Russian Academy of Sciences, ul. Fersmana 14, Apatity, 184200 Russia

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Abstract—Stratigraphic investigations of the Precambrian in Karelia and the Kola Peninsula, which are the type area for the pre-Riphean part of the Proterozoic of northern Eurasia, demonstrate a priority of local stratigraphic scales over regional and interregional schemes and the prime significance of stratotypes of stratigraphic units and their boundaries for substantiating scales of any rank. Data on the structure and subdivision of three pre-Riphean complexes (Saamian, Lopian, and Karelian) of the eastern Baltic Shield are summarized, and a system of subordinate regional subdivisions of two upper complexes assigned to the Upper Archean and the Lower Proterozoic is considered. Attempts to substantiate the event-reflecting boundaries of these subdivisions by isotopic-geochronological data are discussed. The previous studies resulted in the elaboration of the regional chronometric scale only for the Karelian, corresponding to the middle part of the general Precambrian sequence in the region. This scale should be improved in parallel with the regional chronostratigraphic scale.

Key words: *Precambrian, Archean, Proterozoic, Riphean, stratigraphy, boundaries, subdivision, correlation, local and regional scales.*

One of the urgent problems of stratigraphy concerns principles and methods of subdivision and correlation of the Precambrian deposits, especially of the pre-Riphean interval (*Obshchie voprosy* ..., 1979, 1990; *Stratigraficheskoe raschlenenie* ..., 1971; Salop, 1973; V.Z. Negrutsa, 1971a, 1971b, 1988, 1994; Semikhatov, 1979, 1991, 1993; Rankama, 1970; Harland *et al.*, 1990; Plumb, 1991, 1992; Hofmann, 1992). Therefore, the Precambrian stratigraphic investigations in Karelia and the Kola Peninsula that have been conducted for almost 150 years are of particular interest. An urgent task that is very important both for Precambrian stratigraphy and for reconstruction of the early evolution of the Earth's lithosphere is to analyze methodical approaches to the subdivision and correlation of these deposits and to summarize the obtained results. The proposed analysis is based on the summary of published data and my long studies of type sections and boundaries of many local and regional stratigraphic subdivisions of the Precambrian in the eastern Baltic Shield (V.Z. Negrutsa, 1963, 1967, 1971a, 1971b, 1979, 1984; V.Z. Negrutsa *et al.*, 1968; Bogdanov and Negrutsa, 1968).

In the epi-Archean craton of Karelia (the Jatulian continent, according to Väyrynen; *The Precambrian* ... 1963), the Precambrian deposits have sufficiently retained their primary characteristics, and their succession in individual sections and environments of formation can be reconstructed with confidence and are not the subjects of controversy. Existing problems concern the formation of the ancient basement of stratified rocks (Saamides) and, to a lesser degree, the boundaries of stratigraphic subdivisions and the correlation of individual sections. There is lesser progress in solving the problems of the Precambrian stratigraphy of the Kola Peninsula, especially those concerning the Archean deposits and regional correlations because of the more complex tectonics and the higher grade of metamorphism of the Archean deposits, and also due to the predominantly volcanogenic composition of the Lower Proterozoic sequences. However, the Kola Peninsula comprises less heterogeneous tectonic structures of the Archean and Early Proterozoic age; correspondingly, a lesser number of sections of coeval deposits needs to be correlated here. In Karelia, there are more than 30 structures specific in their rock composition reflected in local stratigraphic schemes. In the Kola Peninsula, there are only Pechenga, Keivy, Ust'-Panoi, and Imandra-Varzuga structures of this type, each of which provides some difficulties for correlation. This makes the local and regional stratigraphic schemes less reliable. Therefore, Karelia and Kola Peninsula should be considered in stratigraphic terms as two independent regions. The southern limit of the Kolvitsa-Lapland granulite belt, or the northeastern edge of the conjunction zone of the Karelian and White Sea megablocks can serve as their natural boundary. The only stratigraphic scale for both regions is the interregional correlation scheme.

LOCAL AND REGIONAL STRATIGRAPHIC SCALES FOR THE PRECAMBRIAN OF KARELIA

The recent Precambrian stratigraphy of Karelia is mainly based on investigations aimed at defining local features and elaborating the regional stratigraphic scale. For example, based on his observations in the Ladozhskoe and Onezhskoe lake regions in 1866, P.A. Puzyrevskii suggested subdividing the Precambrian of Karelia into two units correlative with the Laurentian and Huronian formations of the Canadian Shield (the prototypes of the Archean and Lower Proterozoic). In 1877, A.A. Inostrantsev recognized another regional subdivision between two stratigraphic units of Puzyrevskii. Much later, this subdivision was described by Kharitonov (1941) as the Bergaul Formation and by Kratts (1963) as the Lopian, which is now referred to the Upper Archean. The upper of three subdivisions recognized by Inostrantsev was described by P. Eskola (*The Precambrian,* 1963) under the name "Karelian" and was later accepted as a standard for the Lower Proterozoic of northern Eurasia (Shurkin *et al.,* 1979; Kratts *et al.,* 1984; Semikhatov *et al.,* 1991). The lower subdivision of the Precambrian of Karelia is commonly known as the "Saamian Complex" or "Saamian," whose name was suggested by Polkanov and Gerling (1961). In this way, the Lower Precambrian of Karelia was subdivided into three successive complexes: Saamian, Lopian, and Karelian.

The refinement of the Precambrian stratigraphic scale for the region led to the recognition of three subcomplexes of the Karelian complex and two less substantiated subcomplexes of the Lopian complex, both subdivided into local units—groups and formations. Later, some of these units were taken as types of regional subdivisions: groups for divisions or superhorizons, and formations for subdivisions or horizons (*Stratigrafiya i isotopnaya ...,* 1971; Kratts *et al.,* 1984). Thus, the Precambrian stratigraphy of Karelia was developed first from generality to particularity, and then from particular to general concepts based on investigations of actually observed sections and geological contacts regardless of the variable ideas of researchers on their age, rank, regional significance, etc. Thus, the stratotype sections and boundaries of different-rank subdivisions proved to be of prime importance for the Precambrian stratigraphy of Karelia. Finally, the principal significance of local stratigraphic scales for the regional stratigraphy was shown when they were based on the geological survey results. The geological mapping made it possible to recognize reliably the Precambrian subdivisions and elaborate the recent stratigraphic scale of the Precambrian of Karelia (Table 1) (Kratts *et al.,* 1984; *Stratigrafiya nizhnego ...,* 1985; *Postanovleniya MSK ...,* 1992). According to this scale, boundaries of major regional subdivisions correspond to significant structural unconformities and related stratigraphic hiatuses. There are no less than four such boundaries in the composite Precambrian section of Karelia.

The lower boundary of the Karelian Complex, which was recognized by Puzyrevskii and coincides with the Archean-Proterozoic boundary of the current schemes, is the most distinct one. Inostrantsev demonstrated that it corresponds to the Padany unconformity and conglomerate beds of Gelingivaara (Eningivaara) Mountain. As is well known at present (V.Z. Negrutsa, 1971b; T.F. Negrutsa *et al.,* 1985; Kheiskanen *et al.,* 1977; Kheiskanen, 1980), the relationship between the Karelian Complex and underlying formations is most evident in these localities. In the first one, the gently dipping and weakly metamorphosed Jatulian deposits unconformably overlie the heavily dislocated metamorphic Padany schists (Bergaul shists, according to Kharitonov, 1941), which are intruded by granites. In the second locality, there are the pre-Jatulian deposits of the Karelian Complex, the Sariolian (in the interpretation of Eskola, *The Precambrian,* 1963) conglomerates and coeval volcanics, corresponding in the time-range to the Padany unconformity. Correct observations and chronological correlation of the observed objects allowed Inostrantsev to find the localities of the best pronounced stratigraphic boundary in the composite Precambrian section of Karelia and reveal the lateral changes in composition of the basal beds of the Karelian Complex (in the modern terminology). As was shown later (T.F. Negrutsa, 1988, 1990, 1991), these changes evidence that the lower Karelian boundary is diachronous (time-transgressive) and morphologically variable in the lateral direction. Although Inostrantsev was mistaken in referring the youngest Karelian deposits to the Paleozoic, the relationship and succession of these deposits appeared to be correctly defined by him.

The second best pronounced and, correspondingly, reliably defined unconformity, which was also revealed by Inostrantsev, is that between the pre-Karelian stratified high-grade ortho- and parametamorphic rocks and the ultrametamorphic basement. Inostrantsev correlated the former with the Huronian Formation and the latter with the Laurentian Formation of Canada. At present, they are assigned to the Lopian Complex of the Upper Archean and the Saamian Complex of the Lower Archean, respectively. Gilyarova (1974, 1988), as many geologists who worked both before and after her, considered both complexes as pre-Karelian (Archean) in age, while Kratts (1963), who defined the Lopian Complex, referred them to the Lower Karelian and, according to the available data of isotopic-geochronology, considered this interval as the lowermost of three subdivisions of the Proterozoic. This stratigraphic interpretation of the Lopian by Kratts was mainly based on the occurrence of structural unconformity and conglomerates at its base, which were revealed by geological mapping. A careful study of the lower Lopian boundary showed that the pre-Lopian unconformity is indistinct in many places due to ultrametamorphism and tectonic deformations. Therefore, an apparent

Table 1. Stratigraphic scheme for the pre-Vendian deposits of Karelia

Stratigraphic subdivisions										Type area
General		Regional				Local				
		Complex	Subcomplex	Superhorizon	Horizon	Group		Formation		
Proterozoic	Upper (Riphean)	Riphean	Upper							Salmi
			Middle					Salmi		
			Lower							
	1650 ± 50	Karelian	Upper	Vepsian				Shoksha		Shoksha
								Kamennyi Bor		Petrozavodsk
				Kalevian	Ladozhskoe	Ladozhskoe	Besovets			Bol'shoi Yanis-yarvi
	Lower (Karelian)		Middle	Ludian	Onezhskoe	Onezhskoe		Suisari		Northwestern Onezhskoe region
								Zaonezhskii		Pazhi-Kachkomka
				Jatulian				Tulomozero		Pyalozero
					Segozero	Segozero		Medvezh'egorsk		Segozero
								Yangozero		Yangozero
								Maimyarvi		Maimyarvi, Eningivaara
			Lower	Sariolian	Seletskoe	Lower	Tunguda-Nadvoitsy	Seletskoe		Eningilampi, Luzhma, Kanusniemi, Sondaly
								Vermass		
								Ozhiyarvi		Vermass, Okunevoe, Maslozero, Paiozero, Nizhnee, Letnee
				Sumian		Upper		Tunguda		
								Okunevoe		
Archean	2500 ± 50	Lopian	Upper			Gimoly		Surilampi		Kostomuksha, Gimoly, Nyukozero
								Kostomuksha		
			Lower			Kontokk		Ruvinvaara		
								Shurlavaara		
								Niemiyarvi		
								Metasiliciclastic deposits		
		Saamian	Ancient crystalline basement (amphibolite–plagiogranite association represented by pebbles and boulders in the oldest conglomerates of the Lopian)							Northeastern slope of the Lekhta synclinorium, Gangas-Lampi Lake

gradual transition of metamorphosed sedimentary and volcanogenic Lopian deposits into rocks affected by palingenesis and anatexis can be locally observed downsection. However, the available data unambiguously indicate a deep pre-Lopian denudation that exposed the pre-Lopian amphibolite–gneiss–granitoid basement. The structural unconformity between the Lopian and older deposits is evident only from the regional tectonic patterns revealed by geological mapping.

Being poorly exposed, two upper unconformities between the Karelian (Lower Proterozoic) and Riphean (Upper Proterozoic) and between the Riphean deposits and Vendian-Paleozoic sedimentary cover are difficult to observe. These unconformities of uncertain time-range also can be established only by means of geological mapping.

Thus, the composite stratigraphic succession of the Precambrian of Karelia exhibits five structural-lithological complexes separated by unconformities: (1) the Saamian Complex of amphibolite-gneiss-granite association of the ancient metamorphic basement; (2) the Lopian Complex of gneiss-amphibolite-schist association originated in the course of metamorphic alterations of sedimentary-volcanogenic deposits; (3) the Karelian Complex of metasiliciclastic-carbonate-basaltoid association, which marks the terminal stage of metamorphic processes in the region; (4) the Riphean Complex of siliciclastic-basaltoid association of the ancient platform cover; and (5) the Vendian-Paleozoic Complex of the platform sedimentary cover.

It is evident that the Precambrian of Karelia is subdivided on the basis of tectonic criteria. Therefore, it would be more proper to recognize tectonic units of the structural stage rank rather than stratigraphic units of the high-rank. This interpretation of the Precambrian subdivisions of Karelia emphasizes first that the boundaries of the recognized structural-lithological subdivisions are diachronous in the lateral direction, and second, that their manifestation depends on the types of paleotectonic structures in which they are observed. The geological processes determining these boundaries (structural rearrangements, changes in sedimentation environments, breaks in sedimentation and volcanic activity, etc.) are much better pronounced in the active tectonic structures than in less active depressions, where the frequently continuous sedimentation was not affected by tectonic activity. Therefore, boundaries of the stratigraphic subdivisions are more distinct in the first than in the second structures. Obviously, the sections of basins with stable sedimentation are more informative for the stratigraphic reconstruction of successive events in time than those of depressions with an unstable and discontinuous regime of sedimentation. Therefore, the present stratigraphic scale for the Precambrian of Karelia should be considered as preliminary groundwork for further reconstructions.

It should be remembered that this approach to the elaboration of the Precambrian stratigraphic scale is not only unavoidable, but necessary because of the generally low resolution power of the biostratigraphic method for the Precambrian and due to the lack of paleontological records from the Proterozoic deposits of Karelia. Therefore, unconformities, which are tectonic markers of geological history, are of prime importance for the Precambrian stratigraphy of Karelia. This stimulated special comparative historical-geological studies of unconformities (events) and other types of stratigraphic boundaries in the continent–basin facial-paleogeographical profile (V.Z. Negrutsa, 1967, 1971a, 1988; Negrutsa and Negrutsa, 1988). These studies show that the time-ranges of stratigraphic hiatuses (time-gaps) correlative with unconformities become smaller toward the central parts of paleobasins and that the best isochronous markers are the stratigraphic levels of the transgression maxima or the most intensive volcanic impulses. In other words, the most complete and stratigraphically informative sections are those where the hiatuses are insignificant or absent, rather than those where unconformities and hiatuses are best pronounced.

In essence, the investigations in Karelia provide an example of the application of methodology and experience of Phanerozoic stratigraphical studies to the Precambrian successions (V.Z. Negrutsa, 1967, 1971a, 1979, 1984, 1988). The Precambrian investigations were based on the fundamental position suggesting the correspondence of stratigraphic subdivisions to individual natural stages of geological development, which are represented by the cyclic and rhythmic events of transgressions and regressions, on the one hand, and by volcanic-plutonic and structural-metamorphic processes, on the other hand. On this basis, the stratigraphic procedure should include the establishment of a hierarchy of subordinate rhythms and cycles of sedimentation and volcanic activity, the recognition of interchangeable correlation features, and the determination of age and origin of the observed features of layered rocks. This complicated multipurpose procedure of investigations should involve the whole spectrum of phenomena related to the formation and alteration of supracrustal successions (Negrutsa and Negrutsa, 1988). However, this approach is justified, because it provides new advantages to local and regional stratigraphic investigations by using geological events of the Precambrian and evaluating their metrical properties (V.Z. Negrutsa, 1984, 1994). Its essence is the introduction of historical-geological criteria for stratigraphic subdivisions, which allow us to estimate the relative stratigraphic and, when sufficient isotope-geochronological data are available, the "absolute" duration of stratigraphic hiatuses separating adjacent stratigraphic subdivisions (T.F. Negrutsa, 1988, 1991).

LOCAL AND REGIONAL STRATIGRAPHIC SCALES FOR THE PRECAMBRIAN OF THE KOLA PENINSULA

In contrast to Karelia, stratigraphic investigations in the Kola Peninsula are aimed at elaborating local strati-

graphic scales on the basis of geological mapping and correlating them with the Karelian scales taken as the standards. As a result, specific stratigraphic scales have been elaborated for every isolated distribution area of stratified Precambrian rocks of the Kola Peninsula (Zagorodnyi *et al.*, 1964; Belolipetskii *et al.*, 1980; Predovskii, 1980; Melezhik and Predovskii, 1982; *Kol'skaya sverkhglubokaya* ..., 1984; Predovskii *et al.*, 1987; Vrevskii, 1989). The general scheme for the whole peninsula copies the regional scheme of Karelia, which, in essence, is the general scale for the Karelian Complex of both regions (Table 2). The application of the Karelian scale to the Precambrian rock sequences of the Kola Peninsula is possible due to the similarity of lithological and geochemical features of some correlative levels, as well as the succession of geological events and isotope-geochronological data. Despite this, the structure and boundaries of the Saamian are not defined, and there is no adequate accuracy in the subdivision of the Lopian. The most complete and best-studied sections of the Lopian analogues in the Kolmozero-Voron'ya depression and Keivy zone show two- or three-member structure. However, these local stratigraphic subdivisions have neither type sections nor well-established boundaries and are difficult to trace laterally. In other words, all of them are generally composite structural-lithological subdivisions.

In contrast, the Karelian Complex of the Kola Peninsula is better studied in the stratigraphic aspect. The stratigraphic successions of the discrete tectonic structures of the Karelian have been carefully studied and subdivided into independent systems of local units. Correlation of these systems to each other and to the interregional correlation levels (to the stratigraphic subdivisions of the Karelian Complex of Karelia) is ambiguous and controversial (*Stratigrafiya i izotopnaya* ..., 1971; Gilyarova, 1972; *Zemnaya kora* ..., 1978; Kratts *et al.*, 1984; V.Z. Negrutsa, 1984; *Dokembriiskaya geologiya* ..., 1988; *Stratigrafiya SSSR*, 1989). However, there is little or sometimes no difference in opinion when the interregional correlations are substantiated by the comparison of concrete type sections (stratigraphically defined and adequately studied objects) on the basis of a combination of chronologically interchangeable features of geological-historical events and isotope-geochronological data (Pushkarev, 1990).

CORRELATION OF STRATIGRAPHIC SCALES OF KARELIA AND KOLA PENINSULA

In spite of the difference in accepted concepts and methods of correlation, all investigators of the Precambrian of Karelia and Kola Peninsula recognize in these regions five successive rock complexes: Saamian, Lopian, Karelian, Riphean, and Vendian, the latter not being discussed in this work. The structure of the first four complexes is shown in Table 3.

The Saamian Complex is the oldest regional structural-lithological subdivision, which served as a source of clastic material for the succeeding complex. Judging from the composition of pebbles in the oldest conglomerates of the latter, the association of plagiogranitoids (partly gneissoid) and amphibolites, including metagabbroids, was the main constituent of the Saamian. Therefore, the Saamian Complex can be considered as an association of ultrametamorphic rocks of the ancient basement, suggesting that a primitive continental crust of mafic-to-sialic composition was formed at that time. Formations of this type compose central parts of some antiforms and are recorded as restites among younger granitoids and their migmatites.

The Lopian Complex consists of differently metamorphosed sedimentary, volcanogenic, and intrusive rocks formed on the Saamian amphibolite–plagiogranite basement and bounded on the top by the pre-Karelian (pre-Sumian) unconformity. The lower boundary of the complex is defined by the appearance of interbeds of conglomerates and other ancient parametamorphic rocks. However, the tracing of this boundary is hampered by uncertainties concerning the composition of the Saamian Complex and the presence or absence of originally sedimentary deposits among its rocks (in principle, their absence is postulated by the accepted definition of the lower Lopian boundary). Difficulties in defining the upper Lopian boundary are caused first by attempts to substantiate it not by stratigraphic but tectonic events, e.g., by the termination of the post-Lopian diastrophism, whose age relation to the initial stages of the Karelian (Sumian and Sariolian) is ambiguous. Second, the scope of the Sumian and its position in the regional stratigraphic scale are differently evaluated (*Stratigrafiya i izotopnaya* ..., 1971; Kheiskanen, 1980; *Geologiya Karelii*, 1987). Attempts to settle the problem by using radiometric data led to conflicting conclusions (Lazarev, 1987; *Izotopnaya geokhronologiya,* 1989; Levchenko *et al.*, 1994).

The problem can be solved by designating the stratotype sections of the Lopian and Sumian and their boundary stratotypes. As is known, the Gimoly Group was originally chosen as the type sequence of the Lopian (Kratts, 1963). At present, a section of the Kostomuksha iron-ore deposits, which includes two (Karpang and Gimoly) successive groups, can be considered as its stratotype. The stratigraphy of this area has been well studied (Gor'kovets and Raevskaya, 1991) and repeatedly discussed (also during field excursions), but there are still some uncertainties concerning the boundaries of subdivisions.

First, the relationship between basal gneisses of the Lopian and granitoids of the basement is not clear due to the influence of younger granite intrusions (Gor'kovets and Raevskaya, 1991). Second, the Lopian deposits are separated from the overlying metasediments and metavolcanites of the Bol'shozero Formation by a structural unconformity and stratigraphic hia-

Table 2. Stratigraphic scheme for the pre-Vendian deposits of the Kola Peninsula

Regional stratigraphic subdivisions			Correlation of local stratigraphic schemes							
			Structural-facial zones							
			Pechenga		Imandra-Varzuga		Keivy			
Complex	Subcomplex	Superhorizon	Group	Formation	Group, formation		Group, formation			
Riphean	Upper		Kil'din	Karuyarvi Zemlepakhtinskaya	Chapoma					
	Middle			Poropelon Palvina	Terskii					
	Lower			Pyaryayarvi	Turii					
Karelian	Upper			Por'itash Bragino						
			Pil'guyarvi	Matert Lammass Zhdanov	Il'mozero	Upper				
	Middle	Ludian Jatulian	Kolosioki	Salmiyarvi Luchlompol		Lower Upper				
					Umba	Lower	Umba			
			Kuets'yarvi	Pirttiyarvi	Polisarka	Upper Lower	Keivy	Pestsovaya Tundra		
				Kuverneriioki	Seida	Upper Lower				
	Lower	Sariolian	Akhmalakhti	Mayarvi Telekino	Kuksha	Upper Lower		Vykhchurta		
					Purnach	Upper Lower		Chervuta		
Lopian	Polycyclic complex of alternating metavolcanogenic and metasedimentary deposits		Stratigraphic subdivision, chronological sequence, and names of recognized subdivisions are multivariant				Lebyaszh'ya Voron'ya Tundra Polmos Tundra Lyavozero			
Saamian		Ancient crystalline basement (amphibolite–plagiogranite association represented by boulders and pebbles in the oldest conglomerates of the Lopian)								

tus of indefinite duration. The Bol'shozero Formation, which originally served as one of the Sumian prototypes (Kratts, 1963), can be correlated, according to new data, with the post-Sumian deposits that constitute the Sariolian Superhorizon, the second from the base of the Karelian (T.F. Negrutsa *et al.*, 1985). If this is correct, then the hiatus between the Lopian and the oldest deposits of the Karelian Complex in the Kostomuksha region corresponds to the Sumian Superhorizon and to preceding periods of terminal Lopian diastrophism and peneplanation. It is evident that such a hiatus should be very long. In the northeastern slope of the Lekhta synclinorium near Okunevoe Lake, the hiatus between the Lopian and Karelian deposits is known to be less considerable (T.F. Negrutsa, 1971, 1979). In this area, there is one of the most complete sections of the Lopian (the Pebozero section), which demonstrates the entire succession and boundaries of this subdivision (Bogdanov *et al.*, 1968). This valuable section is evidently a possible candidate for the stratotype of the upper Lopian boundary (Bogdanov and Negrutsa, 1968; V.Z. Negrutsa, 1967, 1979; Kratts *et al.*, 1984). Another possible candidate suggested by T.F. Negrutsa and other researchers (Predovskii, 1980; V.Z. Negrutsa, 1984) is the section in the Kola Peninsula, which incorporates the boundary separating the Chervuta Formation of the Keivy Group from the underlying Lebyazh'ya Formation. Of special interest is the fact that the Archean and Proterozoic rocks of this section are bedded with a minor unconformity or even conformably (T.F. Negrutsa, 1991).

Table 3. Stratigraphic scheme for the pre-Vendian deposits of the eastern Baltic Shield

Kratts *et al.*, 1984				*Resolutions MSC*, 1987; *Postanovleniya MSK*, 1992; Semikhatov, 1993; and others		
Complex	Superhorizon	Horizon	Group, formation (stratotype)	Complex	Subcomplex	Superhorizon
			Volokovoi	Riphean	650 ± 20	
			Kil'din			
			Terskii			
			Turii			
		1650 ± 50			1650 ± 50	
Karelian	Vepsian	1850 ± 50	Shoksha	Karelian	Upper	Vepsian
			Petrozavodsk			
		1950 ± 50				
	Livvian	2100 ± 50	Ladozhskoe			Kalevian
	Ludian	Sulsari	Onezhskoe		Middle	Ludian
		Zaonezhskii				
	Jatulian	Tulomozero				Jatulian
		Medvezh'egorsk	Segozero			
		Yangozero				
		Maimyarvi				
	Sariolian		Seletskoe		Lower	Sariolian
	Sumian	2450 ± 50	Vermass			Sumian
			Paiozero			
		2600 ± 100	Ozhiyarvi			
			Tunguda			
			Okunevoe			
					2500 ± 50	
Lopian	Keivy	Vykhchurta	Keivy	Lopian	Upper	
		Chervuta				
	Tundra	Lebyazh'ya	Gimoly			
		Patcherv Tundra	Kontokk		Lower	
		Ponoi				
	3500 ± 100 (?)					
Saamian				Saamian		

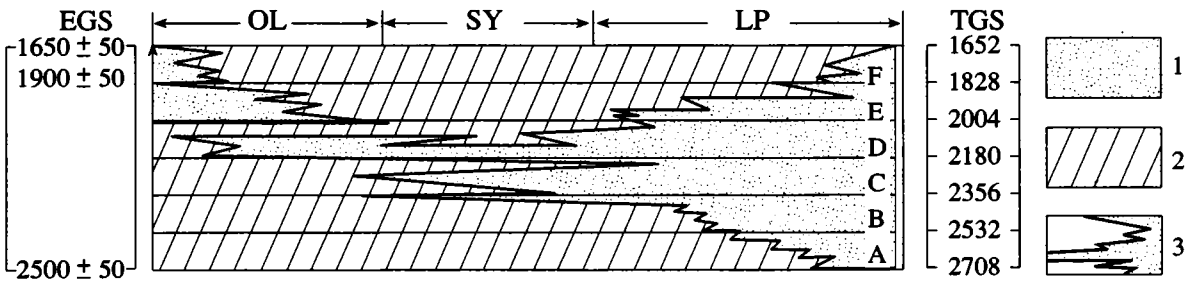

Fig. 1. Structure of the Karelian Complex (Lower Proterozoic) of the Baltic Schield: (1, 2) Karelian Complex: (1) lithological components (sedimentary and volcanogenic deposits); (2) stratigraphic components (hiatuses and unconformities); (3) geological-historical boundaries of formations (events); (A–F) major regional subdivisions (superhorizons) of the Karelian Complex: (A, B) Lower Karelian; (C, D) Middle Karelian; (E, F) Upper Karelian; (EGS) empirical geochronometric scale, Ma; (TGS) theoretical geochronometric scale, Ma; (OL) Onezhskoe–Ladozhskoe section; (SY) Segozero–Yangozero section; (LP) Lekhta–Pechenga section

In the Kostomuksha stratotype section, the Lopian is subdivided into the Karpang and Gimoly groups (Gor'kovets and Raevskaya, 1991). The Pebozero parastratotype section also exhibits the two-member structure of the Lopian. Similar to the Karpang and Gimoly groups, its constituent Tikshozero and Pebozero groups (Bogdanov *et al.*, 1968; Bogdanov and Negrutsa, 1968) are separated by conglomerates with pebble of the Lower Lopian rocks including ferruginous quartzites and metavolcanics. The two-member structure of the Lopian is also recorded in other localities, particularly in the Kolmozero-Voron'ya area of the Kola Peninsula (Belolipetskii *et al.*, 1980; Rybakov *et al.*, 1981; Vrevskii, 1989). Therefore, some researchers are inclined to recognize two interregional stratigraphic subdivisions of the Lopian age. In general, they are similar in structure, comprising a horizon of metasedimentary deposits (with conglomerates) overlain by a komatiite–basaltoid association of volcanics with interbeds of metasedimentary deposits, which are replaced upsection by a dacite–andesite–liparite association with occasional conglomerates, schists, and turbidites (the Padany schists and others). However, the persistence of the time-range of these stratigraphic subdivisions in the lateral direction has not been proved, and the two-member structure of the Lopian of these regions is still speculative.

The Karelian Complex of the whole Kola–Karelia region is subdivided into three subcomplexes, and each of them comprises two superhorizons with subordinate units, such as horizons and local subhorizons (Fig. 1, Table 1). The horizons and subhorizons of the Middle Karelian, which include lateral successions of coeval formations and subformations, can be reliably traced throughout, or most nearly everywhere in, Karelia and Kola Peninsula (Kratts *et al.*, 1984; Makarikhin and Kononova, 1983; Satsuk *et al.*, 1988; V.Z. Negrutsa, 1984; *Stratigrafiya arkheya ...*, 1979; *Geologiya Karelii*, 1987; *Stratigrafiya nizhnego ...*, 1985; *Stratigrafiya SSSR*, 1989; *Dokembriiskaya geologiya*, 1988; and others). The suggested stratotypes of all these subdivisions and boundary stratotypes are not officially accepted so far.

All regional subdivisions of the Karelian are separated by geological events and correspond to complete transgressive-regressive cycles of sedimentation and concrete episodes of magmatism (superhorizons) or to stages (horizons) and phases (subhorizons) of regional transgressions and regressions and volcanic activity. Each subdivision recognized by means of facial (lithogenetic) analysis is fully expressed in continuous or relatively continuous sections. However, not only in the region under consideration but also in other areas of the Precambrian distribution, such sections frequently display controversial positions of boundaries and, hence, unidentical time-ranges of stratigraphic subdivisions of all ranks. The boundaries corresponding to unconformities (in the sections known to be incomplete) along with facially persistent and lithologically homogenous subdivisions are best pronounced and homogenous. It is evident that these sections exhibit only some parts of stratigraphic subdivisions separated by hiatuses of various duration (Fig. 2). The experience of Phanerozoic geology suggests that the problem can be solved by placing greater emphasis on the lower (initial) boundary of a chronostratigraphic subdivision, which is at the same time the upper (terminal) boundary of the preceding subdivision. This would be important for maintaining the uniform principles of elaboration of the Precambrian and Phanerozoic chronostratigraphic frameworks (V.Z. Negrutsa, 1984; Semikhatov *et al.*, 1991; Bekker, 1992; Semikhatov, 1993).

Methodically different approaches to the definition of stratigraphic boundaries lead to the differences both in estimations of time-range of the whole Karelian Complex and its subordinate subdivisions of all ranks and in the determination of chronological limits of natural stages in the Precambrian history of the region.

Karelia and Kola Peninsula show the fragmentary distribution of the Riphean Complex represented by deposits of different lithological-facial types, which have no specific paleobiological characteristics and have been poorly studied by isotopic dating. Therefore,

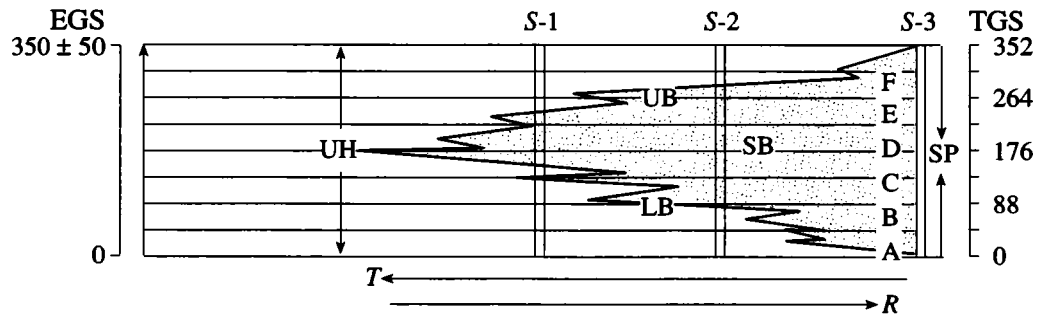

Fig. 2. Structure of the regional stratigraphic subdivision (subcomplex) of the Karelian Complex of the eastern Baltic Shield. Stratigraphic subdivision (SP) of subcomplex rank with subordinate subdivisions (A–F); (SB) stratified geological body (lithological component of the stratigraphic subdivision) with its lower (LB) and upper (UB) boundaries; (UH) unconformity and (or) stratigraphic hiatus (stratigraphic components of the subdivision); (EGS) empirical geochronological scale: (350± 50 Ma is the total stratigraphic range) with local stratigraphic scales incomplete (S-1, S-2) and complete (S-3) geological sections; (TGS) theoretical geochronological scale, Ma; (*T*) direction of transgression; (*R*) direction of regression.

none of the regional and interregional correlation schemes for the Kola-Karelian Riphean is reliable so far. The unanimously defined lithostratigraphic subdivisions of the complex are assigned to different subcomplexes (the Lower, Middle, and Upper Riphean) according to sparse isotopic-geochronological and paleontological data and/or on the basis of historical-geological reconstructions (Tables 1, 2). Leaving aside relevant problems, I should mention that the stratigraphic position of the boundary between Karelian and Riphean complexes in the region is not clear. It is commonly placed at the unconformity separating the metamorphosed and dislocated Karelian deposits intruded by rapakivi granites from the unmetamorphosed flat-lying Riphean cover of the East European platform. However, this interpretation of the boundary meets with two difficulties. First, the rapakivi granites are anorogenic; i.e., they formed after the orogenic processes when the regional metamorphic alterations of the Karelian Complex had been completed. Second, recent radiometric age determinations suggest that these granites were formed at the beginning of the Early Riphean and that the oldest overlying deposits (the Salmi Formation), whose age cannot be precisely determined, correspond to the undivided Lower-Middle Riphean. In this connection, the geological significance and stratigraphic position of the association of siliciclastic deposits and acid volcanics are of special interest. The unmetamorphosed deposits of the association rest on the Karelides with a sharp disconformity and represent an independent stratigraphic subdivision (horizon) recognized by Polkanov (1956) under the name of "the Hogland Formation" and obviously underlying the Salmi Formation.

ON THE ISOTOPIC DATING OF THE PRECAMBRIAN STRATIGRAPHIC BOUNDARIES IN KARELIA AND KOLA PENINSULA

The bulk of isotopic data on the Precambrian formations of Karelia and Kola Peninsula has been obtained for intrusive and high-grade metamorphic rocks. Recently, some reliable values of radiometric ages of slightly altered volcanics hàve been published. The stratigraphic interpretation of these data meets with two problems. First, we should understand which of the possible geological processes is reflected by these data and the relative place and geological-historical significance of this process in a general succession of events in the geological history of the region. The second problem concerns the age relation between the dated objects and main boundaries of the regional stratigraphic scale. As already mentioned, in Karelia and Kola Peninsula, these boundaries are placed at unconformities corresponding to stratigraphic hiatuses of uncertain duration. At the same time, manifestations of volcanism and intrusive magmatism in Karelia and Kola Peninsula mainly occurred in the periods of maximal tectonic extension or compression, which correspond to the maxima of transgressions and succeeding regressions (V.Z. Negrutsa, 1984, 1988). Consequently, the dated objects were formed during the middle and terminal phases of regional transgressive–regressive cycles referred to superhorizons or other stratigraphic units of higher rank. Thus, the magmatic and related events mark the termination, not the beginning (as sometimes is thought), of the formation of geohistorical stratigraphic subdivisions. Therefore, the isotopic age of lower boundaries of large stratigraphic subdivisions can be defined only within broad limits.

It should be noted that statistic peaks of isotopic data, which are sometimes correlated with the maxima of endogenic activity (Pushkarev, 1990), do not necessarily correspond to the transition from one stratigraphic subdivision to another. Therefore, the stratigraphic reconstructions should be based on ages of real geological events and not on the statistic data commonly used in practice. At the current level of knowledge, the last approach cannot provide for the precise dating of geological-historical stratigraphic boundaries. In practice, the isotopic ages of boundaries of the stratigraphic scale for the Precambrian of the eastern

Baltic Shield are determined with a precision of ±50 Ma. However, boundaries in the Archean part of this scale, especially older than 3.0 or 3.1 Ga, are generally dated considerably less precisely. In any case, the isotopic age of the Saamian–Lopian boundary and, correspondingly, the time-range of the Lopian cannot be considered as well-established. Many additional isotopic determinations are needed to date the boundaries of some Karelian subdivisions reliably, although we already have sufficient interpretative material to build some correct models including those based on cycle chronometry (Pushkarev, 1990; V.Z. Negrutsa, 1994). As for the Riphean of Karelia and Kola Peninsula, there are single isotopic age determinations for these deposits that meet the recent requirements. Precisely, this causes problems in assigning local stratigraphic successions to the general scale of the region

The aforesaid suggests that, at the present state of knowledge, the chronometric (isotopic-geochronological) scale can be substantiated only for the Karelian, which is the middle unit of the Precambrian in Karelia and Kola Peninsula. This scale reflects the recent isotopic dates for the boundaries of the corresponding part of the chronostratigraphic scale. Being independent, these two scales should be developed in parallel, by means of mutual addition and control.

CONCLUSION

The composite section of the pre-Vendian part of the Precambrian of Karelia and Kola Peninsula comprises four structural-lithological complexes, which reflect the megacyclic changes in sedimentogenesis and magmatism and are separated by events of diastrophism and denudation. The Saamian and Lopian complexes are referred to the Archean, and the Karelian and Riphean complexes, to the Proterozoic. The three upper complexes are subdivided into regional subcomplexes, and the Karelian and Riphean complexes are additionally subdivided into finer units.

The history of the Precambrian stratigraphic investigations in the region testifies to a priority of the local scales over the regional and interregional scales and demonstrates the principal significance of stratotypes of chronostratigraphic units and their boundaries for substantiating scales of any rank. The standard sections should be the most complete, displaying stratigraphic boundaries defined by successive events in the evolution of sedimentary basins and volcanic activity. The observed unconformities and hiatuses are most helpful for recognizing these subdivisions and for the initial mapping of particular geological bodies and subsequent facial-paleogeographic studies. However, the boundaries of these bodies are usually transgressive in time and variable in space. The Precambrian stratigraphy in Karelia and Kola Peninsula, like in any other region, should be further developed through the improvement and refinement of chronostratigraphic and isotopic-geochronologic scales, which complement each other and, therefore, can and must be refined only in parallel.

Reviewers Yu.R. Bekker and A.I. Zhamoida

REFERENCES

Bekker, Yu.R., Real and False Pecularirties of Precambrian Stratigraphy, *Sov. Geol.*, 1992, no. 2, pp. 106–113.

Belolipetskii, A.P., Gaskel'berg, V.G., Gaskel'berg, L.A., *et al., Geologiya i geokhimiya metamorficheskikh kompleksov rannego dokembriya Kol'skogo poluostrova* (Geology and Geochemistry of Lower Precambrian Metamorphic Complexes of the Kola Peninsula), Leningrad: Nauka, 1980.

Bogdanov, Yu.B. and Negrutsa, V.Z., The Archaean: the Eastern Baltic Shield (Karelia), in *Regional'noe stroenie SSSR. T. I. Stratigrafiya* (Structural Regions of the USSR. Vol. 1: Stratigraphy), Moscow: Nedra, 1968, pp. 78–80.

Bogdanov, Yu.B., Voinov, A.S., Kazak, A.P., and Negrutsa, V.Z., High-Grade Metamorphic Conglomerates of the Eastern Karelia, *Litol. Polezn. Iskop.*, 1968, no. 2, pp. 99–110.

Dokembriiskaya geologiya SSSR (Precambrian geology of the USSR), Leningrad: Nauka, 1988.

Geologiya Karelii (Geology of Karelia), Leningrad: Nauka, 1987.

Gilyarova, M.A., *Stratigrafiya i struktury dokembriya Karelii i Kol'skogo poluostrova* (Precambrian Stratigraphy and Structures of Karelia and Kola Peninsula), Leningrad: Leningrad. Univ., 1972.

Gilyarova, M.A., *Stratigrafiya, struktury i magmatizm dokembriya vostochnoi chasti Baltiiskogo shchita* (Precambrian Stratigraphy, Structures, and Magmatism of the Eastern Baltic Sheild), Leningrad: Nauka, 1974.

Gilyarova, M.A., Precambrian Stratigraphy of the Eastern Baltic Sheild, *Vestn. Leningrd. Gos. Univ.*, 1988, Ser. 7, no. 14, issue 2, pp. 21–32.

Gor'kovets, V.Ya. and Raevskaya, M.B., *Geologiya i metamorfizm zhelezistokremnistykh formatsii Karelii* (Geology and Metamorphism of Iron-Banded Formations in Karelia), Leningrad: Nauka, 1991.

Harland, W.B., Armstrong, R.L., Cox, A.V., *et al., A Geologic Time Scale 1989,* Cambridge: Cambridge Univ., 1990.

Hofmann, H.I., New Precambrian Time Scale: Comments, *Episodes,* 1992, vol. 15, no. 2, pp. 122–123.

Izotopnaya geokhronologiya dokembriya (Isotopic Geochronology of the Precambrian), Leningrad: Nauka, 1989.

Kharitonov, L.Ya., *K stratigrafii i tektonike karel'skoi formatsii dokembriya* (On Stratigraphy and Tectonics of the Karelian Formation of the Precambrian), Leningrad: Leningrad. Geol. Upr., 1941, no. 23.

Kheiskanen, K.I., *Karel'skaya geosinklinal' (litologicheskii analiz)* (Karelian Geosyncline: Lithological Analysis), Leningrad: Nauka, 1980.

Kheiskanen, K.I., Golubev, A.I., and Bondar', L.F., *Orogennyi vulkanizm Karelii* (Orogenic Volcanism in Karelia), Leningrad: Nauka, 1977.

Kol'skaya sverkhglubokaya (The Kola Superdeep Well), Moscow: Nedra, 1984.

Kratts, K.O., *Geologiya karelid Karelii* (Geolgy of Karelides in Karelia), Moscow: Nauka, 1963.

Kratts, K.O., Negrutsa, V.Z., Sokolov, V.A., *et al.*, New Data on Precambrian Stratigraphy in the Soviet Part of the Baltic Shield, *Sov. Geol.*, 1984, no. 7, pp. 105–118.

Lazarev, Yu.I., *Mineral'nye uran-svintsovye vozrasty dokembriya vostochnoi chasti Baltiiskogo shchita* (Uranium–Lead Ages of Minerals from the Precambrian of the Eastern Baltic Shield), Leningrad: Nauka, 1987.

Levchenkov, O.A., Nikolaev, A.A., Bogomolov, E.S., and Yakovleva, S.Z., Uranium–Lead Age of the Sumian Acid Magmatic Rocks in Northern Karelia, *Stratigr. Geol. Korrelyatsiya*, 1994, vol. 2, no. 1, pp. 3–9.

Makarikhin, V.V. and Kononova, G.M., *Fitolity nizhnego proterozoya Karelii* (Lower Proterozoic Phytoliths from Karelia), Leningrad: Nauka, 1983.

Melezhik, V.A. and Predovskii, A.A., *Geokhimiya ranneproterozoiskogo litogeneza* (Geochemistry of the Early Proterozoic Lithogenesis), Leningrad: Nauka, 1982.

Negrutsa, T.F., Section Types and Stratigraphy of Karelides in the Northeast if the Karelian Massif, in *Stratigrafiya i izotopnaya geokhronologiya vostochnoi chasti Baltiiskogo shchita* (Precambrian Stratigraphy and Isotopic Geochronology of the Estern Baltic Shield), Leningrad: Nauka, 1971, pp. 57–65.

Negrutsa, T.F., *Paleogeografiya i litogenez rannego proterozoya oblasti sochleneniya karelid i belomorid* (Early Proterozoic Paleogeography and Lithogenesis in the Junction Zone of Karelides with Belomorides), Leningrad: Leningrad. Gos. Univ., 1979.

Negrutsa, T.F., Reference Sections, Correlation, Ranges, and Stratigraphic Subdividions of the pre-Jatulian Deposits, the Lower Proterozoic of Karelia, in *Stratigrafiya nizhnego dokembriya Karelo-Kol'skogo regiona* (Stratigraphy of the Lower Precambrian in Karelia and Kola Peninsula), Leningrad: Nauka, 1985, vol. 339, pp. 56–66.

Negrutsa, T.F., *Granitsa arkheya i proterozoya na Baltiiskom shchite* (Archaean–Proterozoic Boundary in the Baltic Shield), Apatity: Kol'sk. Fil. Akad. Nauk SSSR, 1988.

Negrutsa, T.F., Pre-Jatulian Interval of the Karelian in the Baltic Shield and Problems concerning the Archaean–Lower Proterozoic Boundary Stratotype, in *Stratigrafiya arkheya i nizhnego proterozoya SSSR* (Archaean–Lower Proterozoic Stratigraphy of the USSR), Ufa: Geol. Inst. Bashkir Nauchn. Tsentr Akad. Nauk SSSR, 1990, pp. 66–68.

Negrutsa, T.F., Historical-Geological Substantiation of the Archaean–Proterozoic Boundary, *Doctoral (Geol.-Mineral.) Dissertation*, St. Peterburg Univ.,1991.

Negrutsa, T.F., Korsakova, M.A., and Ivanov, N.M., Reference Sections of the Sariolian in the Eastern Baltic Shield, in *Stratigrafiya nizhnego dokembriya Karelo-Kol'skogo regiona* (Stratigraphy of the Lower Precambrian in Karelia and Kola Peninsula), Leningrad: Nauka, 1985, vol. 339, pp. 66–78.

Negrutsa, V.Z., An Experience of Study on Facies of Proterozoic (Jatulian) Deposits in the Central Karelia, *Sov. Geol.*, 1963, no. 7, pp. 52–76.

Negrutsa, V.Z., Stratigraphy and Lithogenesis of Middle Proterozoic Deposits in Karelia: Implications to the Problem of Metalliferous Quartz Conglomerates, *Cand. Sc. (Geol.–Mineral.) Dissertation*, Leningrad: All-Union Geol. Inst., 1967, p. 28.

Negrutsa, V.Z., Significance of the Multipurpose Facial-Paleogeographic Method for Subdivision and Correlation of Various Metamorphic Sequences of the Precambrian, in *Stratigrafiya i izotopnaya geokhronologiya dokembriya vostochnoi chasti Baltiiskogo shchita* (Precambrian Stratigraphy and Isotopic Geochronology of the Estern Baltic Shield), Leningrad: Nauka, 1971a, pp. 108–113.

Negrutsa, V.Z., Characteristics of the Sariolian Group Stratotype and Substantiated Position of This Group in the Composite Precambrian Section of Karelia, in *Problemy geologii dokembriya Baltiiskogo shchita i Russkoi platformy* (Problems of Precambrian Geology in the Baltic Shield and Russian Platform), *Tr. VSEGEI*, no. 68, 1971b, pp. 133–152.

Negrutsa, V.Z., Main Subdivisions of the Precambrian Stratigraphic Scale for the Eeastern Baltic Shield, *Dokl. Akad. Nauk SSSR*, 1979, vol. 244, no. 1, pp. 165–169.

Negrutsa, V.Z., *Ranneproterozoiskie etapy razvitiya vostochnoi chasti Baltiiskogo shchita* (Early Proterozoic Stages in Evolution of the Eeastern Baltic Shield), Leningrad: Nedra, 1984.

Negrutsa, V.Z., Principles of Stratifying the Precambrian, *Geol. Geofiz.*, 1988, no. 9, pp. 3–11.

Negrutsa, V.Z., From the Structural-Lithologic Periodization to the Chronometric Stratigraphic Cycles of the Precambrian, in *Obshchie voprosy i printsipy raschleneniya dokembriya* (General Problems and Principles of Subdividing the Precambrian), St. Petersburg: Nauka, 1994, pp. 27–43.

Negrutsa, V.Z. and Negrutsa, T.F., *Istoriko-geologicheskii metod izucheniya dokembriya* (Historical-Geological Method in Studies on the Precambrian), Leningrad: Nedra, 1988.

Negrutsa, V.Z., Bogdanov, Yu.B., and Suslova, S.N., Proterozoic: the Eeastern Baltic Shield, in *Regional'noe stroenie SSSR. T. I. Stratigrafiya* (Structural Regions of the USSR. Vol. 1: Stratigraphy), Moscow: Nedra, 1968, pp. 115–130.

Obshchie voprosy raschleneniya dokembriya SSSR (General Problems of Precambrian Stratigraphy in the USSR), Leningrad: Nauka, 1979.

Obshchie voprosy raschleneniya dokembriya SSSR (General Problems of Precambrian Stratigraphy in the USSR), Ufa: Bashkir Nauchn. Tsentr Akad. Nauk SSSR, 1990.

Plumb, K.A., New Precambrian Time Scale, *Episodes*, 1991, vol. 14, no. 2, pp. 139–140.

Plumb, K.A., New Precambrian Time Scale. Reply, *Episodes*, 1992, vol. 15, no. 2, pp. 124–125.

Polkanov, A.A., *Geologiya khoglandiya-iotniya Baltiiskogo shchita (stratigrafiya, kinematika i magmatizm)* [Geology of the Hoglandian–Jotnian in the Baltic Shield (Stratigraphy, Kinematics, and Magmatism)], Leningrad: Akad. Nauk SSSR, 1956, no. 16.

Polkanov, A.A. and Gerling, E.K., Geochronology and Geological Evolution of the Baltic Shield and Framing Foldbelt, in *Voprosy geokhronologii i geologii* (Problems of Geochronology and Geology), Leningrad: Nauka, 1961, issue 12, pp. 7–102.

Postanovleniya Mezhvedomstvennogo stratigraficheskogo komiteta i ego postoyannykh komissii (Resolutions of the Interdepartmental Stratigraphic Committee and Its Permanent Commissions), St. Petersburg, 1992, no. 26.

Predovskii, A.A., *Rekonstruktsiya uslovii sedimentogeneza i vulkanizma rannego dokembriya* (Reconstruction of Environments of the Early Precambrian Sedimentogenesis and Volcanism), Leningrad: Nauka, 1980.

Predovskii, A.A., Melezhik, V.A., Bolotov, V.V., *et al., Vulkanizm i sedimentogenez dokembriya severo-vostoka Baltiiskogo shchita* (Precambrian Volcanism and Sedimentogenesisin the Northeastern Baltic Shield), Leningrad: Nauka, 1987.

Pushkarev, Yu.D., *Megatsikly v evolyutsii sistemy kora-mantiya* (Megacycles in Evolution of the Crust–Mantle System), Leningrad: Nauka, 1990.

Rankama, K., Global Precambrian Stratigraphy: Background and Principles, *Scientic,* 1970, vol. 105, no. 8, pp. 382–391.

Rybakov, S.I., Svetova, A.I., Kulikov, V.S., *et al., Vulkanizm arkheiskikh zelenokamennykh poyasov Karelii* (Volcanism in the Archaean Greenstone Belts of Karelia), Leningrad: Nauka, 1981.

Salop, L.I., *Obshchaya stratigraficheskaya shkala dokembriya* (General Stratigraphic Scale of the Precambrian), Leningrad: Nedra, 1973.

Satsuk, Yu.I., Makarikhin, V.V., and Medvedev, P.V., *Geologiya yatuliya onegosegozerskogo vodorazdela* (Geology of the Jatulian in the Onezhskoe–Segozero Watershed), Leningrad: Nauka, 1988.

Semikhatov, M.A., New Stratigraphic Scale of the Precambrian in the USSR: Analysis and Lessons, *Izv. Akad. Nauk SSSR, Ser. Geol.,* 1979, no. 11, pp. 5–22.

Semikhatov, M.A., Current Concepts of General Subdivision of the Precambrian, an Analysis, *Izv. Akad. Nauk SSSR, Ser. Geol.,* 1991, no. 8, pp. 3–13.

Semikhatov, M.A., General Subdivision of the Precambrian: Comparison of the Latest Scales, *Stratigrafiya. Geol. korrelyatsiya. T. I,* 1993, no. 1, pp. 6–20.

Semikhatov, M.A., Shurkin, K.A., Aksenov, E.M., *et al.,* New Stratigraphic Scale of the Precambrian in the USSR, *Izv. Akad. Nauk SSSR, Ser. Geol.,* 1991, no. 4, pp. 3–13.

Shurkin, K.A., Dobrokhotov, M.N., Zagorodnyi, V.D., *et al.,* The Early Precambrian in the East European Platform (Stratigraphy and Correlation), in *Stratigrafiya arkheya i nizhnego proterozoya SSSR* (Archaean–Lower Proterozoic Stratigraphy of the USSR), Leningrad: Nauka, 1979, pp. 5–23.

Stratigraficheskoe raschlenenie i korrelyatsiya dokembriya severo-vostochnoi chasti Baltiiskogo shchita (Stratigraphic Subdivisions and Correlation of the Precambrian in the Northeastern Baltic Shield), Leningrad: Nauka, 1971.

Stratigrafiya arkheya i nizhnego proterozoya SSSR (Archaean–Lower Proterozoic Stratigraphy of the USSR), Leningrad: Nauka, 1979.

Stratigrafiya i izotopnaya geokhronologiya dokembriya vostochnoi chasti Baltiiskogo shchita (Stratigraphy and Isotopic Geochronology of the Eastern Baltic Shield), Leningrad: Nauka, 1971.

Stratigrafiya nizhnego dokembriya Karelo-Kol'skogo regiona (Stratigraphy of the Lower Precambrian in Karelia and Kola Peninsula), Leningrad: Vses. Geol. Inst., 1985.

Stratigrafiya SSSR. Nizhnii dokembrii. Evropeiskaya chast' SSSR (Stratigraphy of the USSR: Lower Precambrian in the European Part of the USSR), Moscow: Nedra, 1989.

The Precambrian, Vol. 1, New York: Wiley and Sons, 1963. Translated under the title *Dokembrii Skandinavii,* Moscow: Mir, 1967.

Vrevskii, A.B., *Petrologiya i geodinamicheskie rezhimy razvitiya arkheiskoi litosfery (na primere severo-vostochnoi chasti Baltiiskogo shchita)* [Petrology and Geodynamic Evolution of the Archaean Lithosphere(the Northeastern Baltic Sheild as an Example)], Leningrad: Nauka, 1989.

Zagorodnyi, V.G., Mirskaya, D.D., and Suslova, S.N., *Geologicheskoe stroenie pechengskoi osadochno-vulkanogennoi serii* (Geological Structure of the Sedimentary-Volcanogenic Oechenga Group), Moscow-Leningrad: Nauka, 1964.

Zemnaya kora vostochnoi chasti Baltiiskogo shchita (The Earth Crust of the Eastern Baltic Sheild), Leningrad: Nauka, 1978.

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Paleozoic Brachiopod Assemblages of the West Siberian Lowland

N. P. Kul'kov* and L. G. Peregoedov**

**Joint Institute of Geology, Geophysics, and Mineralogy, Siberian Division, Russian Academy of Sciences, Universitetskii pr. 3, Novosibirsk, 630090 Russia*
***Siberian Research Institute of Geology, Geophysics, and Mineral Resources, Krasnyi prospekt 67, Novosibirsk, 630104 Russia*

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Abstract—The Upper Ordovician–Lower Carboniferous brachiopod assemblages are described and the basic framework of the Paleozoic stratigraphy in the West Siberian Lowland is substantiated by the stratigraphic distribution of these fossils. A long-term biogeographic connection of the West Siberian basin with southern basins of the Salair and Altai Mountains and also with northern basins of the Vaigach, Taimyr, and Siberian platforms is suggested. It was shown that analogues of biostratigraphic units that are established in the indicated orogenic areas can be also defined, based on brachiopod assemblages, in the Paleozoic sequences of the West Siberian Lowland.

Key words: *brachiopods, Paleozoic, stratigraphy, stages, geologic sequence, horizons, biogeography.*

The leading role in the elaboration of stratigraphic scales of the Ordovician, Silurian, and Devonian deposits in the Salair and Altai Mountains belongs to brachiopods. Brachiopod-based stratigraphic schemes proved to be reliable and have retained their basic features since the 1950s–1960s; they have simply been refined.

Originally, the Paleozoic stratigraphic scale of the West Siberian Lowland was based mainly on foraminifers traditionally used in the stratigraphy of unexposed territories (Bogush *et al.*, 1975). Later, various groups of fossil macrofauna, brachiopods included, were used along with microfossils. The first brachiopod finds were recorded in 1976 in Borehole Malaya Icha-4 (depth interval of 4009–3901 m). Brownish gray and dark gray limestones recovered by this borehole were dated back to the late Ludlovian–Pridolian, though the brachiopods were identifined to be the Silurian in age (Bogush *et al.*, 1980). Unfortunately, it was impossible to revise the collection of these brachiopod remains, because geologists from the Industrial–Geological Enterprise *Novosibirskgeologiya* passed them to many paleontologists, and, thus, the collection was completely lost.

Considerable progress in brachiopod studies was attained after introducing the core catcher "Nedra" to drilling practice, which significantly increased the recovery of cores from great depths and the probability of brachiopod finds. Brachiopods were mainly collected by L.G.Peregoedov and G.D. Isaev (Siberian Research Institute of Geology, Geophysics, and Mineral Resources).

The preservation of brachiopods in the West Siberian Lowland is generally better than that of brachiopod remains characteristic of sequences in surrounding mountains. This allowed us to study in many cases the inner structure of shells and to identify their taxa and age more reliably.

At present, there is a voluminous database on brachiopods from the West Siberian Lowland (particularly from its southeastern part). Fifty-five brachiopod species were described in detail. Our descriptions can be found in various publications. Many of the species described are guide fossils of global or interregional significance.

The purpose of this work was to summarize all the data available, to outline the framework of the stratigraphic scale of the Middle Paleozoic stages in the West Siberian Lowland, and to estimate the brachiopod potential for correlation of West Siberian units with the well-known biostratigraphic units of adjacent orogenic regions, such as the Salair and Altai Mountains in the south and the Vaigach, Taimyr, and Siberian platforms in the north.

The necessity to perform this work is evident from the recently published stratigraphic scheme (*Stratigrafiya* ..., 1990), which is based on conflicting data on macro- and microfauna and includes several undivided intervals: Venlockian–Ludlovian, Pridolian–lower Lochkovian, Lochkovian–Pragian, Emsian–Frasnian, and Frasnian(?)–Famennian. Such a degree of stratigraphic resolution is inadequate. It is regrettable that the stratigraphic chapter in the above-cited work lacks new data on brachiopods, which are well described in the same publication and suggest an opportunity to subdivide the Lower Devonian into stages.

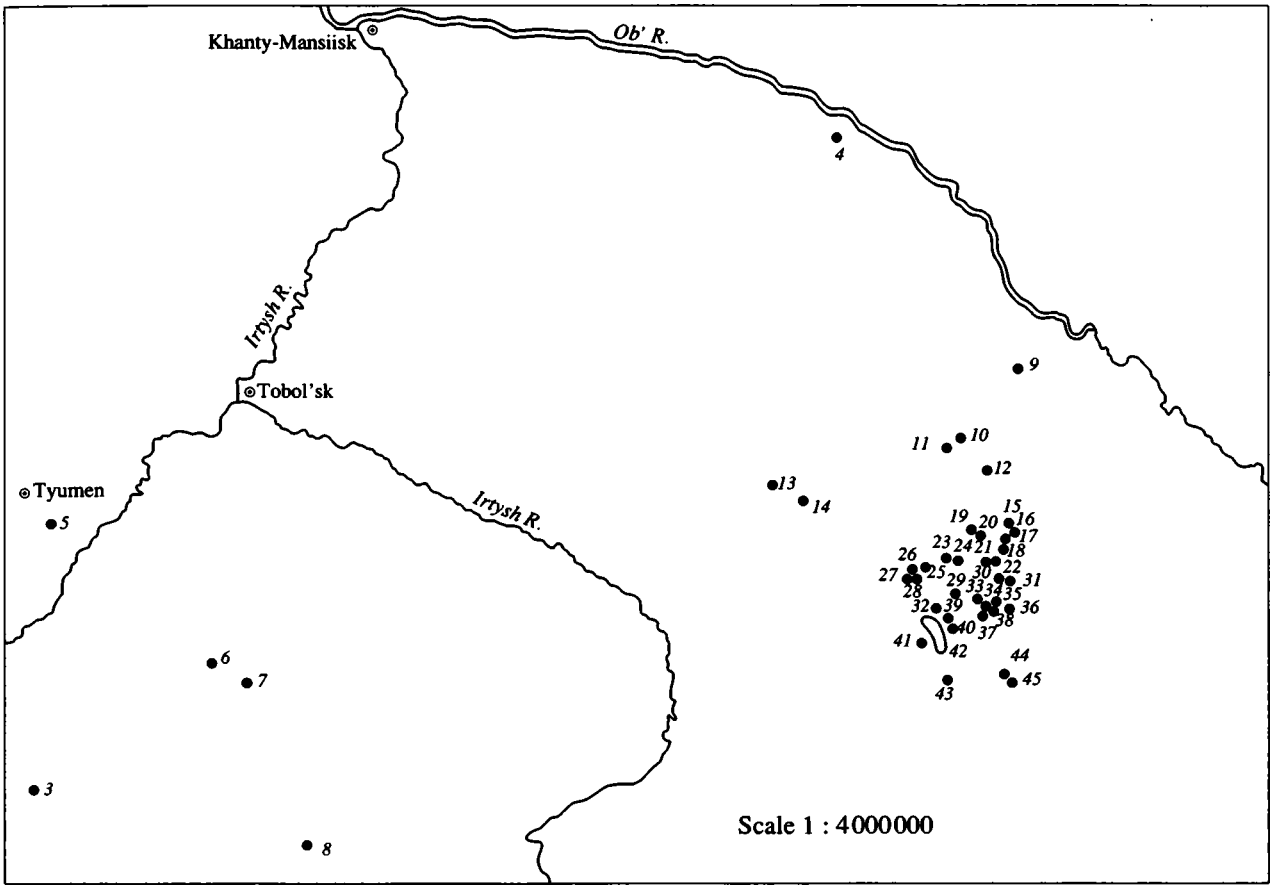

Fig. 1. Localities of boreholes, discussed in the paper.
(*1, 2*) Yutermal'-15 and Zapadno-Novogodnyaya-210 located in the Taz River basin north of area shown; (*3*) Lebyazh'evskaya-2; (*4*) Medvedevskaya-110; (*5*) Borovskaya-4P; (*6*) Ishim-4P; (*7*) Western Ishim-2P; (*8*) Ryavkinskaya-5; (*9*) Sel'skaya-1; (*10*) Myl'dzhin-56; (*11*) Pologaya-1; (*12*) Luginetskaya-170; (*13*) Ellei-Kagal-1; (*14*) Rechnaya-282; (*15*) Severo-Ostaninskaya-10; (*16*) Severo-Ostaninskaya-17; (*17*) Zapadno-Ostaninskaya-443; (*18*) Zapadno-Ostaninskaya-445; (*19*) Pel'ginskaya-1; (*20*) Pel'ginskaya-2; (*21*) Gerasimovo-9; (*22*) Gerasimovo-16; (*23*) Archin-49; (*24*) Archin-58; (*25*) Vodorazdel'naya-2; (*26*) Ellei-Igai-2; (*27*) Ellei-Igai-3; (*28*) Ellei-Igai-4; (*29*) Kulginskaya-140; (*30*) Severo-Kalinovaya-25; (*31*) Severo-Kalinovaya-27; (*32*) Zarechnaya-1; (*33*) Yuzhno-Tabaganskaya-133; (*34*) Yuzhno-Tabaganskaya-134; (*35*) Yuzhno-Tabaganskaya-136; (*36*) Kazanskaya-8; (*37*) Solonovskaya-41; (*38*) Solonovskaya-43; (*39*) Nadezhdinka-2; (*40*) Malaya Icha-17; (*41*) Maizass-1; (*42*) Malaya Icha-4, 7, 22, and 27; (*43*) Yuzhno-Tarskaya-2; (*44*) Kasman-2; (*45*) Kasman-10.

The present paper covers this gap for the Upper Silurian and Lower–Middle Devonian. Our subdivision is based mainly on materials from the reference parametric boreholes (Maizass-1, Zapadno-Ostaninskaya-443, Malaya Icha-22), which recovered thick rock sequences with brachiopods at several contiguous levels. Brachiopods from 33 other shallower boreholes were also studied (Fig. 1). We were able to detect reliably units of the stage rank in some sections. These units do not form a complete succession because of significant stratigraphic gaps in the deposits. Wenlockian and Ludlovian brachiopods have not been found so far, and data on the Upper Devonian brachiopods are scarce. Therefore, different portions of the stratigraphic scheme proposed here (Fig. 2) are incomparable in their resolution ability and substantiation degree. We hope that new materials will result in specification and improvement of the scale.

THE ORDOVICIAN SYSTEM

The Upper Ordovician

The Ashgilian Stage. Ordovician deposits in the southeastern part of the West Siberian Lowland were first described by Isaev *et al.* (1990), who detected them in Borehole Myl'dzhin-56 in the depth interval of 2508–2759 m. The deposits are represented by sandstones, claystones, green-colored lenticular limestones, green foliated calcarenites and calcisiliciliths, greenish dolomites, dolomitized and globular limestones, and dolomitic sandstones and siltstones. The incomplete thickness of this unit, which was named the Pavlovka Sequence (after the Pavlovka Settlement in the Tomsk region), is 176 m. The age of the Pavlovka Sequence was defined, based on corals, stromatoporoids, bryozoans, and conodonts, as the Middle–Late Ordovician. Underlying and overlying strata are unknown.

In the interval of 2524–2578 m of the Borehole Myl'dzhin–56, Isaev found poorly preserved brachiopods, among which N.P. Kul'kov identified *Doleroides* cf. *sibiricus* (Andr.), *Hesperorthis* sp. 1, *Rostricellula* aff. *subrostrata* Nikif., and *Rostricellula* sp. The first form is similar to species characteristic of the Dolbor Horizon of the Siberian platform, whereas the second one reveals some similarity with *Hesperorthis evenkiensis* Nikif. from the same horizon. The third form is close to species from the upper part of the Mangazeya Horizon and from the Dolbor Horizon of the Siberian platform. The fourth form cannot be compared with any known species because of poor preservation. This brachiopod assemblage suggests the Late Ordovician (early Ashgilian) age of the host rocks and allows them to be correlated with the Dolbor Horizon of the Siberian platform. This is supported by some bryozoan species identified by A.M. Yaroshinskaya.

A similar brachiopod assemblage was found in Borehole Zapadno-Novogodnyaya-210 in the northern part of the West Siberian Lowland. The black clayey locally pyritized limestones from the depth interval of 4100–4085 m yielded here *Doleroides* cf. *sibiricus* (Andr.), *Hesperorthis* sp. 2, and *Rostricellula* sp. The first and third forms are identical to those found in Borehole Myl'dzhin-56, whereas *Hesperorthis* sp. is different. Nonetheless, the Zapadno-Novogodnyaya and Myl'dzhin assemblages are approximately synchronous and suggest the Late Ordovician age. Thus, we can outline the correlation level for the Upper Ordovician deposits accumulated in different areas of the West Siberian Lowland.

THE SILURIAN SYSTEM

Lower Silurian[1]

The Llandoverian Stage. In the southeast of the West Siberian Lowland, the Llandoverian deposits were first established based on the find of the brachiopod *Virgianella* sp. in the dark gray clayey limestones recovered in the depth interval of 2856–2862 m of Borehole Severo-Ostaninskaya-10 (Kul'kov, 1991). Previously, these deposits were referred to the Upper Devonian (Saev *et al.*, 1987) on the basis of unilocular foraminifers.

Virgianella sp. belongs to the genus widespread in the upper Llandoverian Stage of the Vaigach Island, Polar Urals, Tien Shan, and South China. Beds with *Virgianella* sp. of the West Siberian Lowland are most likely correlative with the Filipp'el' Horizon of the Polar Urals and Vaigach, where this unit contains the relative species *V. vaigatschensis* Nikif. et Sap. (Beznosova, 1991). Tabulates found in the depth interval of 2783–2910 m of Borehole Severo-Ostaninskaya-10 suggest the Wenlockian age of the host rocks (Dubatolov *et al.*, 1990). Older Llandoverian deposits in the West Siberian Lowland are so far unknown.

THE UPPER SILURIAN

The Wenlockian and Ludlovian stages

Brachiopods from deposits of these stages have not yet been found. The age of the units was defined based on the Wenlockian–Ludlovian tabulate assemblage from cores of Borehole Vodorazdel'naya-2 (Dubatolov *et al.*, 1990). In other boreholes, the Wenlockian (Borehole Medvedevskaya-110, depth interval of 3885–3448 m; Borehole Pologaya-1, depth interval of 2700–2608 m) and Ludlovian (Borehole Malaya Icha-4, depth interval of 4600–4104 m) tabulate assemblages are here detected.

The Ludlovian Stage incorporates the Bol'shaya Icha unit at the base of the Borehole Maizass-1 section (depth interval of 3892–3650 m) composed of basic lava flows and tuff beds (Stepanov *et al.*, 1985). The age of this unit is inferred from its position under the undoubtedly Upper Silurian (Pridolian) deposits with various faunal remains (*Silur i devon ...*, 1990). The Bol'shaya Icha unit proper contains only Actinopterygii fragments of no stratigraphic significance.

The Pridolian Stage

Pridolian deposits with the most complete paleontologic characteristics were penetrated by Borehole Maizass-1. Their thickness is 358 m (depth interval of 3650–3237 m). Pridolian deposits are united into the Maizass Formation composed of gray pelitomorphic and detrital limestones, marls, and black calcareous shales (Stepanov *et al.*, 1985). There are also tuff interbeds and intercalations of basaltic and andesite–porphyritic lava flows. Faunal remains are represented by rugose corals, tentaculites, bryozoans, brachiopods, ostracods, vertebrates (telodonts), and conodonts.

Gratsianova (1985) was the first to describe brachiopods from Borehole Maizass-1 and to identify the Ludlovian age of rocks in the depth interval of 3542–3257 m and "probably the older Llandoverian–Wenlockian age" of rocks from the depth interval of 3609–3571 m. Somewhat later, a group of researchers (Stepanov *et al.*, 1985) published the geological section of this borehole and subdivided its deposits into three units: the Ludlovian Bol'shaya Icha (depth interval of 3892–3650 m), Pridolian Maizass (interval of 3650–3237 m), and Lochkovian Lesnaya (interval of 3237–2810 m) formations. This group also studied various taxa of fauna sampled from the borehole section. The assumption on the presence of Llandoverian–Wenlockian deposits in this section was not confirmed. All the rocks, which had previously been considered as Ludlovian and older, appeared to be of the Pridolian age.

A more thorough study of six faunal groups strengthened the belief that the Maizass Formation

[1] The Lower Silurian, in our meaning, spans the Llandoverian Stage, and the Upper Silurian comprises all other Silurian stages (Kul'kov and Ivanovskii, 1978).

comprises only Pridolian strata (*Silur i devon ...*, 1990). A somewhat conflicting inferrence is based on the conodont fauna. According to Astashkina (1990), conodonts from the lower beds of the formation indicate its late Pridolian–Lochkovian age. In the recent version of the stratigraphic scale (*Stratigrafiya paleozoiskikh ...*, 1990), the last inference is accepted, and the entire Maizass Formation is referred to the Pridolian–lower Lochkovian stages. Some paleontologists place the Maizass Formation at the base of the Devonian and consider it to be of the early Lochkovian age (Saev *et al.*, 1990).

The Maizass brachiopod assemblage includes *Aegeria mariaformis* Lenz, *Hemitoechia*(?) sp., *Atrypoidea phoca* (Salter), *Gracianella plicumbra* Johnson et Boucot, *Howellella mercuriformis* Kulk., *Spirinella majzassica* Kulk., and *Greenwieldia*(?) *nucleolata* (Hall). The Pridolian interval is subdivided into the *Atrypoidea phoca* (lower) and *Gracianella plicumbra* (upper) zones reflecting the successive deepening of the Maizass sea.

The age analogues of the Maizass Formation are established in several boreholes: in the Malaya Icha-4 section (depth interval of 4104–3901 m), by corals and stromatoporoids; in the Zarechnaya-1 section (interval of 3962–3090 m), by conodonts; in the Kasman-10 section (interval of 2965–2845 m), by brachiopods *Aegeria mariaformis* Lenz, *Atrypoidea* sp., and *Greenwaldia*(?) *nucleolata* (Hall); in the Malaya Icha-22 section (interval of 3870–3200 m), by the Ludlovian–Pridolian species *Pseudocamaratoechia nuculaeformis* Kulk.; and in the Sel'skaya-1 section (interval of 2709–2704 m), by the presence of species of the *Pseudohomeospira* genus characteristic of the Pridolian Greben' Horizon in Vaigach Island and the Kal'vitsa Formation in the Novaya Zemlya Archipelago (Nikiforova, 1970; Modzalevskaya, 1989).

Pridolian deposits are widespread in the southeast of the West Siberian Lowland, from the Maizass-1 locality in the south to the Sel'skaya-1 locality in the north. In southern areas, they are mostly represented by black calcareous shales, and in the northern areas, by various limestones.

THE DEVONIAN SYSTEM

The Lower Devonian

The section recovered in the depth interval of 3545–2855 m of the parametric Borehole Zapadno-Ostaninskaya-443 represents a reference section for the Lower Devonian. Brachiopods from this borehole were first studied by Gratsianova (1985), who dated rocks in the interval of 3454–2873 m as Middle Devonian (mainly Givetian) in age. A special study of cores from this borehole was performed by Saev *et al.* (1988), who also substantiated their Eifelian–Givetian age.

Our age interpretation of this section is different (Kul'kov and Peregoedov, 1989). In our work, we substantiated the Early Devonian age of rock from the depth interval of 3545–2855 m, subdivided the section into stages, and detected conformable contact between the Lower Devonian deposits and underlying conventionally dated Upper Silurian strata (interval of 3988–3545 m). Analogues of the Lockhovian, Pragian, and Zlichovian stages were also defined in other boreholes, and, thus, the succession of stages of the Lower Devonian in the southeastern areas of the West Siberian Lowland was outlined. These new data stimulated paleontologists to revise their concepts on the age of the deposits in question. For instance, Dubatolov *et al.* (1990) arbitrarily referred the main part of the section recovered from Borehole Zapadno-Ostaninskaya-443 to the Emsian. Saev *et al.* (1990) also followed our interpretation of the considered section. However, defining the Maizass Formation (based on lithology) at its base, they ascribed the latter to the Lochkovian Stage of the Lower Devonian.

Recently, many researchers began to consider the regional correlation units of the Devonian in the West Siberian Lowland as horizons corresponding to stages. These horizons are equivalent either to previously established lithostratigraphic units (formations, sequences) or to some parts of sections, whose lithostratigraphic features are not discriminated. Four horizons defined in the Lower Devonian are often inconsistent with the regulations recommended by the Stratigraphic Code. Our critical comments on this problem will be given below, in addition to a description of stratigraphic brachiopod assemblages.

The Lochkovian Stage

Before proceeding to the characteristics of the Lockhovian Stage, we will briefly dwell on the Silurian–Devonian boundary in the southeastern areas of the West Siberian Lowland. It is impossible to trace this boundary using brachiopods, because there are no boreholes where strata with brachiopod assemblages contact each other or are spatially contiguous. In the Upper Silurian Maizass Formation penetrated by Borehole Maizass-1, brachiopods are diverse (see above), whereas the overlying Lower Devonian Lesnaya Formation lacks these fossils. The opposite situation is observed in Borehole Zapadno-Ostaninskaya-443, where analogues of the Maizass Formation are characterized by an extremely impoverished brachiopod assemblage, whereas the Lower Devonian part of the section is sufficiently rich in brachiopod remains. Despite the fact that the Pridolian and Lochkovian brachiopod assemblages were found in different boreholes, it can be stated that the Silurian–Devonian transition in the southeastern part of the West Siberian Lowland is gradual, without a hiatus, as is supported by data from Borehole Malaya Icha-22 (see below). The gradual transition is also confirmed by the absence of a biostratigraphic gap between the above-mentioned assemblages, as well as by the similarity of clay–car-

bonate rocks formed in the terminal Silurian–earliest Devonian. The conformable contact between the deposits in question is also evident from the correlation of the Pridolian and Lochkovian deposits of the West Siberian Lowland with the boundary units of the Salair and Altai Mountains, i. e., with the Sukhoi and Chernyi Anui formations of the Silurian and the Tom'-Chumysh and Remnevo formations of the Devonian. The correlative taxons of the Pridolian are represented by *Pseudocamarotoechia nuculaeformis* Kulk., *Gracianella* sp., and *Spirinella majzassica* Kulk., and those of the Lochkovian are represented by *Iridistrophia johnsoni* Smith, *Lanceomyonia* sp., and *Protathyris sibirica* Zintch.

Thus, dark gray calcareous shales, limestones, and marls recovered in the depth interval of 3545–3110 m of Borehole Zapadno-Ostaninskaya-443 belong to the Lochkovian Stage. Several members are defined here on the basis of lithologic data; five of them (II–VI) correspond to the stratigraphic interval under consideration (Saev *et al.*, 1988). Its brachiopod assemblage includes *Taimyrrhynx paricostatus* (Tcherk.), *Lanceomyonia confinis* (Barr.), *Delthyris gibbosus* (Barr.), *Mesodouvillina ivaensis* (Barr.), *Spinatrypina margaritoides* Rzon., and *Isorthis inostranzewi* (Peetz).

Assemblages similar in age but of somewhat different composition were found in Borehole Solonovskaya-41 (interval of 3023–2956 m): *Cypidula* cf. *subgaleata* Kulk., *Taimyrrhynx paricostatus* (Tcherk.), *Ancillotoechia ancillans* (Barr.), *Spinatrypina margaritoides* Rzon., *Navispira virginia* (Amsd.), *Cyrtina kazi* (Havl.), *C. praecedens* Kozl., and *Protathyris* sp. In Borehole Malaya Icha–22 (3194–2796 m), this assemblage includes *Iridistrophia johnosoni* Smith, *Aesopomum* cf. *sibiricus* (Aleks.), and *Protathyris sibirica* Zintch.

Isaev *et al.* (1992a) referred one part of the deposits recovered from Borehole Malaya Icha-22 (interval of 3194–2870 m) to the new Kyshtovka Horizon incompatible with any known lithostratigraphic unit. The horizon was named after the Kyshtovka Settlement, near which the borehole was drilled. The composition of fauna in the stratotype lacks the regional species: its taxons are either characteristic of the Tom'-Chumysh Horizon of the Salair Range or represented by cosmopolitan species allowing the direct correlation of these deposits with the Lochkovian Stage of the standard stratigraphic scale. Therefore, the Kyshtovka Horizon is an unsuitable independent unit. In addition, its geological and faunal relationships with the Upper Silurian beds and overlying Armich Horizon, which was proposed by the same authors and referred to the Pragian Stage, remain unclear.

In Borehole Malaya Icha-22, the Armich Horizon is reported to be at the depth interval of 2870–2796 m, but its validity is not substantiated. Brachiopods and ostracods from rocks of this and deeper (3194–2870 m) intervals include species representing in total a single Lochkovian assemblage (Kul'kov and Peregoedov, 1989; Savina, 1993).

Deposits from the depth interval of 3496–3010 m in Borehole Zapadno-Ostaninskaya-443, which we consider as an equivalent of the Lochkovian Stage, Isaev *et al.* (1992a) and Savina (1993) ascribe to the Armich Horizon of the Pragian Stage without any evidence supporting this view.

The Pragian Stage

Deposits of this stage in Borehole Zapadno-Ostaninskaya-443 are defined in the depth interval of 3132–2925 m based on the presence of *Isorthis inostranzewi* (Peetz.), *Mesodouvillina* sp., *Taimyrrhynx pasicostatus* (Tcherk.), *T. taimyricus* (Nikif.), *Spinatrypina margaritoides* Rzon., and *Cyrtina praecedens* Kozl. The following forms are stratigraphically important here: the first species, which became extinct in the Pragian just as in the Salair and Altai Mountains; the third species, which is transient from the Lochkovian (the Tolbat Beds) to the Pragian (the Daksan Beds) in Taimyr; and the fourth species characteristic of the Pragian deposits in Taimyr (the Zlobin Horizon) and the Verkhoyansk region (the upper Sette-Daban Subformation). In Taimyr, *T. taimyricus* is also present higher in the section, in deposits of the local *Favosites regularissimus* Zone, now known as the Dolgan Beds. *Spinatrypina margaritoides* is spread through the entire Lower Devonian section in the considered region, though, in the Salair Ridge, its distribution is restricted by the Malyi Bachat Horizon. *Cyrtina praecedens* Kozl. is mainly present in the Lochkovian.

Rocks that were penetrated in the interval of 3104–3043 m of Borehole Yuzhnyi Tabagan-136 (recovered thickness is 46 m) and contain *Taimyrrhynx taimyricus* (Nikif.) and *Caplinoplia embryo* (Barr.) are arbitrarily referred to the Pragian Stage. This inference is mainly based on the presence of *C. embryo,* whose distribution is limited by the Pragian.

Brachiopod assemblages, which we interpret to be of the Pragian age, were also found in other boreholes. In the Kazanskaya-8 locality (interval of 2897–2842 m), the assemblage includes *Isorthis inostranzewi* (Peetz.), *Aesopomum regularis* Lens, *Taimyrrhynx glomerosus* (Amsd.), *Desquamatia* sp., *Cyrtina praecedens* Kozl., and *Nucleospira* sp.; in the Kasmanskaya-2 locality (interval of 2904–2800 m), *Anoplia elongata* Johnson, *Taimyrrhynx paricostatus* (Tcherk.), *Cyrtina kazi* Havlicek, and *Spinatrypa lazutkini* (Aleks.); in the Yuzhnaya Tara-2 locality (interval of 2961–2958 m), *Ambocoelia* sp.; in the Zapadno-Ostaninskaya-445 locality (interval of 2956–2951 m), *Taimyrrhynx globosus* (Amsd.), *T.* aff. *paricostatus* (Tchern.), and *Delthyris* sp.; in the Nadezhdinka-2 locality (interval of 2936–2780 m), *Cepidula* ex gr. *optata* (Barr.), *G.* cf. *rara* (Nikif.), *Glossinotoechia gracianovae* Kulk., *Uncinulus gurjevskensis* Kulk., *Desquamatia* sp. and *Janius* sp.;

and in the Severo-Ostaninsakaya-17 locality (interval of 3077–3973 m), *Uncinulus gurjevskensis* Kulk. and *Ambocoelia* sp.

Isaev *et al.* (1992a) referred deposits corresponding to our Pragian Stage to the Armich Horizon. Initially, the Armich Formation and its stratotype (dark gray bioclastic limestones) were established in Borehole Yuzhnyi Tabagan-134 (Krasnov *et al.*, 1988), which recovered only 47 m (interval of 3100–3053 m) of Paleozoic deposits comprising only part of the Pragian Stage. Later, the 576-m-thick section recovered from Borehole Zapadno-Ostaninsakaya-443 (interval of 3496–2920 m) was selected to represent the stratotype of the Armich Formation. The section of Borehole Yuzhnyi Tabagan-134 was recommended as the parastratotype (Saev *et al.*, 1990).

The Armich Horizon in Borehole Zapadno-Ostaninsakaya-443 was defined only within the scope of the middle (!) subformation of the Armich Formation (Isaev *et al.*, 1992a), which, however, lacks such a subdivision. Only lower (interval of 3495–3018 m) and upper (interval of 3018–2920 m) subformations were originally defined (Saev *et al.*, 1990). There is also an opinion that the Armich Horizon corresponds to the lower Armich Subformation (Savina, 1993). Taking into account such a wide spectrum of views, we consider the "Armich Horizon" as an invalid unit that should be abandoned.

The Emsian Stage

The lower Emsian Substage. The upper part of the section in Borehole Zapadno-Ostaninskaya-443 (interval of 2920–2855 m) is crowned by deposits of the lower Emsian Stage correlated now with the Zlichovian Stage of the Czech Republic. These deposits are similar in lithology (organogenic-detrital limestones) to the underlying Pragian and Lochkovian deposits (down to the depth of 3496 m), and it is not incidental that they were united into a single lithostratigraphic unit—the clay–carbonate "Armich" Formation. It is impossible to discriminate the lithology of this unit and to divide it into subformations (see above).

The lower Emsian brachiopod assemblage in this borehole includes *Xistostrophia* sp., *Gypidila kayseri* (Peetz), *Trigonirhynchia ventricosa* (Aleks.), *Taimyrrhynx taimyricus* (Nikif.), and *Howittia* sp. Brachiopods are accompanied by the diverse Tabulata assemblage including *Tiverina subcrassa* Dubat. et Isaev (Isaev *et al.*, 1992b). The conodont species *Pandorinellina exigua* (Philip) also occurs at this level.

A lower Emsian brachiopod assemblage of substantially different composition was found in Borehole Yuzhnyi Tabagan-133 (depth interval of 3084–3071 m), where it consists of *Areostrophia*(?) sp., *Gypidula kayseri* (Peetz), *Taimyrrhynx taimyricus* (Nikif.), *Uncinulus gurjevskensis* Kulk., *Spinatrypina margaritoides* Rzon., *Carinatina syrmatica* I. Breivel, *Navispira virginia* (Amsden), *Xenospirifer gurjevskensis* (Rzon.), *Delthyris subgibbosa* (Barr.), *Nucleospira* sp., *Schizophoria* sp., and *Ambocoelia* sp. Like in Borehole Zapadno-Ostaninskaya-443, the coral form *Tiverina subcrassa* Dubat. et Isaev was recorded here (Isaev *et al.*, 1992b).

Deposits of the considered stratigraphic level in the section of Borehole Pel'ginskaya-1 (depth interval of 3146–3134 m) yielded *Cymostrophia* sp., *Xistostrophia* sp., *Nurochonetes grandis* (Bubl.), *Trigonirhynchia ventricosa* (Aleks.), *Taimyrrhynx taimyricus* (Nikif.), *Uncinulus gurjevskensis* Kulk., *Spinatrypina margaritoides* Rzon., *Navispira* sp., *Cyrtina* sp., *Howellella* sp., and *Nucleospira* sp. These deposits also contain *Xenospirifer gurjevskensis* (Rzon.) in Borehole Pel'ginskaya-2 (depth interval of 3140–3130 m); *Cymostrophia* sp., *Nurochonetes* sp., and *Xenospirifer* cf. *gurjevskensis* (Rzon.) in Borehole Archin-49 (depth interval of 3204–3104 m); *Cymostrophia* sp. A. *Spinatrypina margaritoides* Rzon., *Desquamatia* sp, and *Xenospirifer gurjevskensis* (Rzon.) in Borehole Archin-58; and *Nurochonetes grandis* (Bubl.) in Borehole Solonovskaya-43 (depth interval of 3064–2973 m).

The lower Emsian deposits recovered by all these boreholes yielded *Xenospirifer gurjevskensis* (Rzon.). This species is typical of the Salair region, and this allows the deposits to be referred to the well-known Salairka Horizon. Isaev *et al.* (1992b) defined the Solonovskaya Horizon, named not after the lithostratigraphic unit (synonymous formation), but after the respective prospect area. The interval of 3150–2960 m in Borehole Solonovskaya-43 was suggested to be the horizon stratotype. Here, the lower boundary of the horizon corresponds to the base of the Armich Formation, which is established in this borehole, whereas the upper boundary coincides with the Paleozoic–Mesozoic erosion contact. Thus, it appears that the incomplete (without upper layers) Armich Formation corresponds in this borehole to the Solonovskii Horizon of the lower Emsian Substage, which appears to be inacceptable.

Only *Nurochonetes grandis* (Bubl.), characteristic of the Emsian Sardzhal' Horizon in Kazakhstan, was identified among brachiopods from Borehole Solonovskaya-43. The generic and specific composition of ostracods found here (Isaev *et al.*, 1992b) differs from that typical of the Solonovskii Horizon (Savina, 1993). Conodonts are represented by *Polygnathus dehiscens* (the Pragian Stage) appearing at the base of the section, by its successor *P. gronbergi*, and by *Pandorinellina exigua* appearing at the base of the Solonovskii Horizon. A similar distribution of *P. dehiscens* and *P. exigua* is also recorded in Borehole Malaya Icha-4.

The Upper Emsian Substage

Brachiopods have not yet been found in deposits of this substage in the southeastern part of the West Sibe-

Table 1. Different views on the subdivision of deposits obtained from Borehole Malaya Icha-4

Depth, m	Bogush *et al.*, 1980	Dubatolov *et al.*, 1984	Dubatolov *et al.*, 1990	Isaev *et al.*, 1992b
2600		Givetian Stage (basal part)	?	
2800	Middle Devonian	"Eifelian Stage"	Givetian Stage (lower part)	
3000				Biazinka Horizon, upper Emsian
3200				
3400	Lower Devonian	Lower Devonian		Solonovskii Horizon, lower Emsian
3600			Lochkovian and Pragian stages	Pragian Stage
3800			?	
4000	Pridolian Stage		Pridolian and partly Lochkovian stages	
4200		Ludlovian (upper part) and Pridolian stages		
4400	Ludlovian Stage		Ludlovian Stage (upper part)	
4600				

rian Lowland. Deposits of this age are arbitrarily outlined only in Borehole Malaya Icha-27 (P-2990) based on the occurrence of *Gypidula* sp., *Vagrania* (*Mimatrypa*) cf. *flabellata* (Roem.), and *Ambocoelia* sp. A brachiopod form similar to *V.* (M.) *flabellata* is characteristic of the upper Emsian and Eifelian; therefore, an unambiguous age identification is impossible.

By other faunal remains, such as foraminifers, ostracods, stromatoporoids, tabulate corals, tentaculites, and conodonts, the deposits in question are united into the Nadezhdinka Horizon, later renamed into the Biazinka Horizon (Isaev *et al.*, 1992b). The subdivision of upper Emsian, Middle Devonian, and Upper Devonian deposits into horizons is inferred from the data on the first deep boreholes Malaya Icha-4 and Luginetskaya-170 spaced at a distance of 170 km and located in the Novosibirsk and Tomsk regions, respectively. Various views on the subdivision of sections in these boreholes are presented in Tables 1 and 2.

The stratotype of the Biazinka (Nadezhdinka) Formation was suggested to be in Borehole Malaya Icha-4, whereas the stratotype of the horizon of the same name is in Borehole Luginetskaya-170. Lists of various faunal groups from the formation and horizon stratotypes differ in different publications (Dubatolov *et al.*, 1990; Isaev *et al.*, 1992b). It appears that the stratotype of the Biazinka Formation comprises the Solonovskii and Biazinka horizons (Table 1), the latter corresponding to the lesser part of the Biazinka Formation. Here, we again face the discrepancy between the scopes of formation and horizon. In Borehole Luginetskaya-170, the stratotype of the Biazinka Horizon is shown as a horizon overlain with a hiatus (depth of 3862) by the stratotype of the Gerasimovo Horizon of the Givetian Stage. This hiatus corresponding to the Eifelian is believed to be of the regional type; in addition to Borehole Luginetskaya-170, it is also recorded in Borehole Malaya Icha-4 and Gerasimovo-9 (Isaev *et al.*, 1992b).

However, there are data contradicting the existence of this hiatus. Recently, we established the widespread Eifelian deposits with *Lazutkinia mamontovensis* (see below). It should also be remembered that deposits above the hiatus in Borehole Luginetskaya-170 incorporate the upper Emsian Tabulata assemblage and representatives of the *Tiverina* genus, which is unknown for the moment beyond the Lower Devonian (Dubatolov *et al.*, 1990). Previously, the "Eifelian" Stage comprising the Emsian and Eifelian proper was established in Borehole Malaya Icha-4 above the assumed hiatus. In Borehole Gerasimovo-9, Isaev *et al.* (1992b) referred the lower part of the section (depth interval of 3042–2982 m) to the Biazinka Horizon of the upper Emsian, whereas higher strata (depth interval of 2982–2910 m, the stratotype of the Gerasimovo Formation) were ascribed to the Givetian Stage. Saev (1992), who studied foraminifers, does not discriminate these parts of the section and considers deposits in the depth interval of 3100–2946 m as belonging to the upper part of the Givetian Stage. Thus, none of the viewpoints on the subdivision of sections suggests a hiatus in sedimentation. To prove this idea, further investigations of various faunal groups are needed.

Table 2. Different views on the subdivision of deposits obtained from Borehole Luginetskaya-170

Depth, m	Bogush *et al.*, 1981	Dubatolov *et al.*, 1984	Krasnov *et al.*, 1988	Dubatolov *et al.*, 1990	Saev *et al.*, 1992	Isaev *et al.*, 1992b	Savina, 1993
2400	Famennian Stage	Famennian Stage	Luginetskaya Formation (stratotype), upper Frasnian–basal Tournaisian	Luginetskaya Formation, Frasnian(?)–Famennian			Luginetskii Horizon (stratotype), Upper Devonian
2600							
2800	Frasnian Stage	Frasnian Stage (upper part)		?			
3000							
3200				Middle Devonian	Gerasimovo Horizon (stratotype), Givetian Stage		Gerasimovo Horizon, Givetian Stage
3400							
3600	Givetian Stage	Givetian Stage		upper Emsian Substage			
3800							
	Eifelian Stage			lower Emsian Substage		Biazinka Horizon (stratotype), upper Emsian	Biazinka Horizon, upper Emsian
	Pragian (?) Stage	Pragian (?) Stage		Pragian (?) Stage		Solonovskii Horizon, lower Emsian	

THE MIDDLE DEVONIAN

The Eifelian Stage

Deposits of the Eifelian Stage are mainly represented by dark gray, black, and dark brown clayey and, less commonly, gray massive reefal limestones with rare shale and siltstone interbeds. Peregoedov (1986) was the first to establish the Eifelian brachiopod assemblage in the massive limestones recovered in the depth interval of 3005–2806 m of Borehole Malaya Icha-7 and to refer these rocks to the facies of the back-reef lagoon. These deposits are known as the "Malaya Icha Limestone." Later, the age range of this unit was widened, and the term was used in the genetic meaning (Dubatolov *et al.*, 1990). The lower part of the recovered section (depth interval of 3126–3005 m), which consists of dark gray bedded clayey limestones with indeterminable brachiopod remains, was formed, in Peregoedov's opinion, in open shelf environments.

Peregoedov listed the following brachiopods: *Chonetes* sp., *Gypidula* sp., *Ivdelinia* cf. *acutolobata* (Sandb.), *I. mesoplicata* Rzon., *Desquamatia* (*Variatrypa*) *pesterevskiensis* Rzon., *Carinatina syrmatica* I. Breivel, *Vagrania* sp., and *Branikia*(?) *snegrensis* Pereg. (Peregoedov, 1990). The assemblage is similar to that from the Pesterevo Limestone, which is incorporated, as a reefal facies, into the Mamontovo Horizon of the Eifelian Stage of the Salair region. The conclusion on the Eifelian age of the Malaya Icha Limestone (*sensu stricto*) is in conflict with data on microfauna, which suggest the Frasnian age of deposits recovered from Borehole Malaya Icha-7 (Dubatolov *et al.*, 1984; Zadorozhnyi, 1987).

Later, brachiopods typical of the Mamontovo Horizon proper of the Salair region were discovered in the southeastern part of the West Siberian Lowland (Kul'kov and Peregoedov, 1993). In boreholes Ellei-Igai-3 (depth interval of 3022–2992 m) and Kulginskaya-140 (depth interval of 3166–3162 m), brachiopods are represented by *Lazutkinia mamontovensis* (Laz.) confined to dark gray clayey limestones. The form arbitrarily identified as *Lazutkinia*(?) sp. was recorded in Boreholes Rechnaya-282 (depth interval of 2915–2910 m) and Gerasimovo-16 (depth interval of 2939–2899 m). The Eifelian species *Desquamatia* (*Variatrypa*) *pesterevskiensis* Rzon. and *Leptathyris gryphis* Siehl were found in Borehole Ellei-Kagal'skaya-1 (3310–3230 m), where they are accompanied by the Mamontovo stromatoporoid assemblage identified by S.N. Makarenko (Saev, 1990).

Savina (1993) united the Eifelian deposits into the Ellei-Igai Horizon, named after the Ellei-Igai prospect area, where the horizon stratotype is in the interval of 3750–3525 m of Borehole Ellei-Igai-2. The deposits are composed of globular muddy limestones with lenticles of calcirudites and bio- and lithoclastic limestones. Any affinity of these rocks to any lithostratigraphic unit (formation) is unknown. Ostracod, foraminifer, stromatoporoid, and tentaculite assemblages are reported from this horizon. Deposits from the interval of 4166–3530 m were first referred to the Eifelian Stage *sensu stricto*, including analogues of the upper Emsian and Eifelian strata proper (Dubatolov *et al.*, 1984). Later, the upper Emsian (the Biazinka Horizon) was assigned to the interval of 4170–3750 m (Isaev *et al.*, 1992b). The post-Eifelian deposits from the intervals of 3525–

3116 and 3116–3048 m are dated by foraminifers as the Givetian and Frasnian, respectively (Zadorozhnyi, 1987). Thus, if this dating is correct, then there is no place for a hiatus corresponding to the Eifelian in Borehole Ellei-Igai-2.

The Givetian Stage

On the basis of brachiopods, analogues of the Givetian Stage are arbitrarily defined. Gratsianova (1985) identified the Givetian species *Emanuella subumbona* (Hall) from gray massive limestones recovered in the interval of 2774–2768 m of Borehole Malaya Icha-17. We discovered the same species in the section of Borehole Severo-Kalinovaya-25 (interval of 3152–3032 m), where its shells form mass accumulations. In Borehole Ellei-Igai-4, macrofaunal remains are extremely rare. However, brownish massive limestones from the interval of 3134–3127 m yielded poorly preserved brachiopod shells, among which representatives of the Stringocephalidae (the Givetian brachiopod group) were identified.

Saev *et al.* (1992) united Givetian deposits into the Gerasimovo Horizon, named after the corresponding formation, whose 70-m-thick stratotype was established in the interval of 2982–2910 m of Borehole Gerasimovo-9 (Krasnov *et al.*, 1988). However, the Gerasimovo Horizon stratotype, having the conventional thickness of 700 m, was defined in the interval of 3862–3134 m of Borehole Luginetskaya-170, and, hence, it is unclear whether this interval comprises the Gerasimovo Formation and whether the top beds of the formation and horizon coincide. Most likely, they do not coincide, because the basal beds of the overlying Luginetskaya Formation and synonymous horizon referred to the Upper Devonian also occupy different stratigraphic levels (Table 2). In view of these facts, practical application of these stratigraphic units is difficult (the Herasimovo Horizon) or unfeasible (the Luginetskii Horizon).

THE UPPER DEVONIAN

The Frasnian and Famennian Stages

No brachiopod remains were found in deposits referred to these stages in many boreholes drilled in the West Siberian Lowland. Gratsianova (1985) listed the early Famennian brachiopods *Camarotoechia* ex gr. *zadonica* Nal., *Cyrtospirifer* cf. *zadonicus* Ljasch., and *C.* ex gr. *archiaci* (Vern.) identified by A.I. Lyashenko from the basal layers in Borehole Borkovskaya-4P (interval of 3041–2981 m). Higher strata in this borehole yielded brachiopods of the Tournaisian Stage.

Savina (1993) united the Upper Devonian rocks of the southeastern part of the West Siberian Lowland into the so-called Luginetskii Horizon. The stratotype of the Luginetskaya Formation, dated back to the late Frasnian–early Tournaisian (Krasnov *et al.*, 1988), was selected in the interval of 2978–2487 m of Borehole Luginetskaya-170, and the stratotype of the horizon corresponding to the Late Devonian was placed in the interval of 3134–2484 m of the same borehole (Table 2). Discrepancy between the formation and horizon ranges, findings of representatives of the Early Givetian Tabulata genus *Tiverina* in the top layers of the Givetian Stage (Dubatolov *et al.*, 1990), and vague relationships with underlying and overlying deposits exclude the possibility of using of the Luginetskii Horizon as a valid biostratigraphic unit. The Upper Devonian units defined in Borehole Luginetskaya-170 mainly on the basis of unilocular foraminifers need to be further substantiated.

In Boreholes Nizhnii Tabagan-17 and 18 and others, the Upper Devonian deposits are more reliably substantiated by conodonts (Aksenova and Astashkina, 1990).

THE CARBONIFEROUS SYSTEM

The Lower Carboniferous

The Tournaisian Stage. Deposits with Early Carboniferous brachiopods are widespread in the West Siberian Lowland. They are recorded in its southwestern, southeastern, and northern areas. Gratsianova (1985) mentioned Tournaisian brachiopod assemblages from several sections drilled in the southwestern West Siberian Lowland. In Borehole Borkovskaya-4P, the upper Famennian deposits (interval of 3041–2981 m) are overlain by rocks (2981–2940) with early Tournaisian brachiopods: *Aulacella* cf. *interlineata* (Sow.), *Schuchertella valentinae* Sok., *Plicochonetes* cf. *poljenowi* (Tolm.), *Avonia* cf. *inflata* (Sok.), *Semiproductus irregularicostatus* (Krest. et Karp.), *Tylothyris* sp., *Hunanospirifer* sp., *Unispirifer* sp., *U.* cf. *praeulbanensis* (Bubl.), *Syringothyris*(?) sp., *Brachythyris* sp., *Torynifer*(?) sp., *Retzia tykhtaensis* Besn., and *Girtyella* cf. *injensis* Besn.

The Tournaisian brachiopod assemblages from other boreholes have a slightly different composition and include *Plicochonetes elegans* (Kon.), *Productus* sp., *Cyrtospirifer jeffersonensis* Well., *Spirifer sibiricus* Leb., and *Sp.* ex gr. *tornacensis* Kon. (identifications by R.N. Benediktova) occurring in gray and dark gray limestones in the interval of 1627–1625 m of Borehole Ryavkinskaya-5; *Schuchertella* sp., *Camarotoechia* sp., *Unispirifer* sp., *Syringothyris* sp., and Athyrididae typical of dark gray limestones from the interval of 3034–3030 m of Borehole Ishim-4P; *Rugosochonetes* cf *hardrensis* (Phill.), *Unispirifer* cf. *osipovensis* (Besn.), *Spirifer* cf. *taigensis* Besn., and *Mesoplica* cf. *abyschevensis* Sar. incorporated in gray and dark gray limestones from the interval of 2181–2051 m of Borehole Western Ishim-2P; and also *Marginatia* sp., *Plicochonetes* sp., *Megachonetes* sp., *Tylothyris* sp., *Spirifer* cf. *acceptus* Besn., *Unispirifer osipovensis* (Besn.), and *Torynifer* sp. confined to dark gray and black limestones from the interval of 1438–

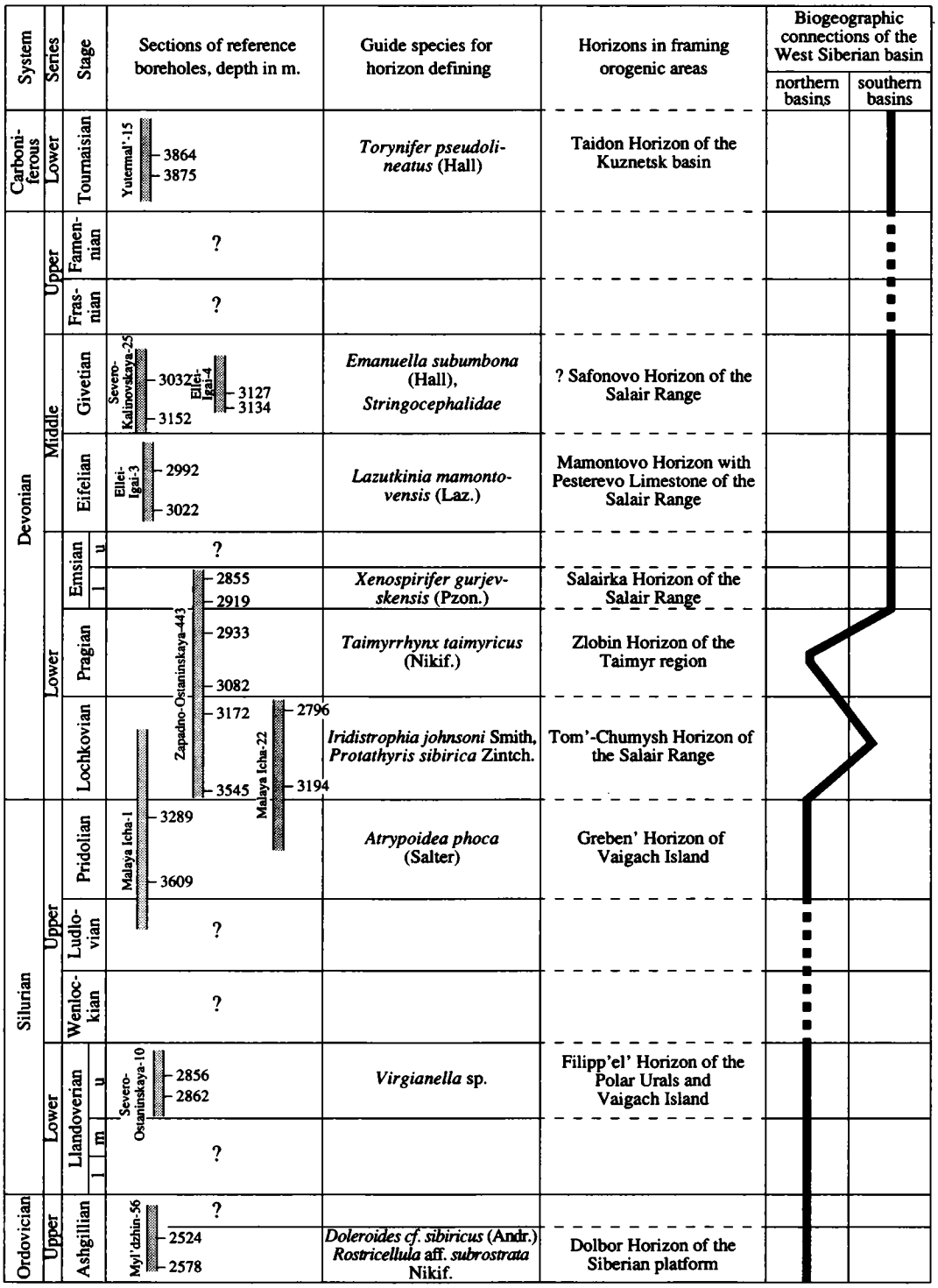

Fig. 2. Scheme of stage subdivision of Paleozoic deposits in the West Siberian Lowland based on brachiopods and biostratigraphic analogues of horizons in the framing orogenic areas. (l) lower, (m) middle, and (u) upper.

690 m of Borehole Lebyazh'evskaya-2 (Gratsianova, 1984).

In the southeastern West Siberian Lowland, deposits with the Early Carboniferous Productidae and *Torynifer* sp. (identifications by R.T. Gratsianova) were reported only from Borehole Severo-Kalinovaya-27 (interval of 3148–3140 m). The interval of 3510–3135 m is composed here of gray and dark gray clayey–calcareous siltstones and fine-grained sandstones with muddy limestone interbeds and represents the stratotype of the Kekhoreg Sequence (Krasnov *et al.*, 1986).

The Tournaisian brachiopod assemblage consisting of *Schuchertella* sp., *Rugosochonetes hardrensis* (Phill.), *Pustula* aff. *dengisi* (Nal.), *Eumetria* sp., *Torynifer pseudolineatus* (Hall), *Brachythyris* cf. *suborbicularis* (Hall), Athyrididae, and *Girtyella*(?) sp. was also identified from the interval of 3875–3864 m of Borehole Yutermal'-15 in the northern West Siberian Lowland (Kul'kov *et al.*, 1991).

Rugosochonetes hardrensis (Phill.), *Unispirifer osipovensis* (Besn.), *Torynifer pseudolineatus* (Hall), and *Brachythyris* cf. *suborbicularis* (Hall) are the most important taxons, which allow the interregional and wider correlation of the Tournaisian deposits. At present, stratigraphically higher Carboniferous brachiopod assemblages are unknown in the West Siberian Lowland. The terminal Lower, Middle, and Upper Carboniferous deposits are mainly dated here based on foraminifers.

CONCLUSION

Studied brachiopod assemblages imply that the West Siberian sea basin had a biogeographic connection with the northern sea basins of Vaigach Island, Taimyr, and the Siberian platform, as well as with southern basins of the Salair and Altai Mountains. From the Late Ordovician to the Early Devonian, the connection with northern basins was closer (Fig. 2). Later, beginning in the Emsian, the influence of fauna from southern sea basins increased and remained stable until the Early Carboniferous. Many brachiopod species from the Salair and Altai regions, zonal forms included, freely migrated into the West Siberian basin.

Taking into consideration the peculiarities of biogeographic connections, we believe that it is reasonable to use the analogues of stratigraphic units, first established in the fringing orogenic areas, also in the stratigraphy of the West Siberian Lowland, particularly in its southeastern areas. This proposition is based on at least two facts. First, the defined brachiopod assemblages are free of specific (endemic) taxons, which could compose peculiar fauna independently evolving in the West Siberian Lowland. Here, the assemblages consist mainly of already well-known species from neighboring regions, or from cosmopolitan guide taxons that allow correlation of local units with the stages of the standard scale. Second, most of the local stratigraphic units were established, as was mentioned above, ignoring the rules of stratigraphic nomenclature.

At present, the stratigraphic subdivisions, which can be identified in the relatively uniform clay–carbonate Paleozoic sequence of the West Siberian Lowland (Fig. 2), are analogues of the following units : (1) the Dolbor Horizon of the lower Ashgillian Stage in the Siberian platform; (2) the Filpp'el' Horizon of the upper Llandoverian in the Polar Urals and Vaigach Island; (3) the Greben' Horizon of the Pridolian Stage in Vaigach Island; (4) the Tom'-Chumysh Horizon of the Lochkovian in Salair Range; (5) the Zlobin Horizon of the Pragian Stage in Taimyr; (6) the Salairka Horizon of the lower Emsian in the Salair region; (7) the Mamontovo Horizon with the Pesterevo Limestone of the Eifelian in the Salair Range; (8) probably, the Safonovo Horizon of the Givetian Stage in the Salair Range; and (9) the Taidon Horizon of the Tournaisian Stage in the Kuznetsk basin. The regional peculiarities of brachiopod assemblages from these units are reflected in the names of most guide species, e.g., *waigatschensis, taimyricus, gurjevskensis* (Fig. 2). Every horizon defined in the West Siberian Lowland does not represent, as a rule, the whole range of the respective unit because of the fragmentary core material and scarce paleontological data.

Nonetheless, the studied parts of horizons help to subdivide particular borehole sections and correlate synchronous stratigraphic levels in various prospect areas, which is very important for geologic practice.

The characteristic brachiopod species defined allow a wider stratigraphic correlation of coeval deposits to be performed. The biostratigraphic correlation of the Lower Devonian sections of the West Siberian Lowland and Siberian platform is already accomplished (Kul'kov and Matukhin,1990).

Reviewer B.S. Sokolov

REFERENCES

Aksenova, L.M. and Astashkina, V.F., The Group Conodontophorida, in *Stratigrafiya paleozoiskikh otlozhenii yugo-vostoka Zapadno-Sibirskoi plity* (Stratigraphy of Paleozoic Deposits in the Southeast of the West Siperian Platform), Novosibirsk: Nauka, 1990, pp. 131–146.

Astashkina, V.F., Conodonts, in *Silur i devon yugo-vostoka Zapadno-Sibirskoi plity* (Silurian and Devonian in the Southeast of the West Siberian Platform), Moscow: Nauka, 1990, pp. 63–69.

Beznosova, T.M., Biostratigraphy and Brachiopods from Silurian Deposits in the Northeast of the European Part of the USSR, *Cand. Sci. (Geol.-Mineral.) Dissertation*, Ekaterinburg: Inst. Geol. Geochem., Ural. Division, Russian Acad. Sci., 1991.

Bogush, O.I., Bidzhakov, V.I., Dubatolov, V.N., *et al.*, Composition and Age of Paleozoic Deposits in Well Luginetskaya-170 (Tomsk Region), in *Paleozoi Zapadno-Sibirskoi nizmennosti i ee gornogo obramleniya* (Paleozoic of the West Siberian Lowland and Its Orogenic Framing), Novosibirsk: Nauka, 1981, pp. 3–36.

Bogush, O.I., Bochkarev, V.S., and Yuferev, O.V., *Paleozoi yuga Zapadno-Sibirskoi ravniny* (Paleozoic in the South of the West Siberian Plain), Novosibirsk: Nauka, 1975.

Bogush, O.I., Dubatolov, V.N., Dubatolova, Yu.A., *et al.*, Stratigraphy and Lithology of the Middle Paleozoic Deposits: Data on Well Malaya Icha-4 (Novosibirsk Region), in *Devon i karbon Aziatskoi chasti SSSR* (Devonian and Carboniferous in the Asiatic Part of the USSR), Novosibirsk: Nauka, 1980, pp. 4–37.

Dubatolov, V.N., Krasnov, V.I., Ratanov, L.S., *et al.*, Lithostratigraphic Subdivision and Correlation of Sections Recovered by Parametric and Prospect Drillholes, in *Stratigrafiya*

paleozoiskikh otlozhenii yugo-vostoka Zapadno-Sibirskoi plity (Stratigraphy of Paleozoic Deposits in the Southeast of the West Siberian Platform), Novosibirsk: Nauka, 1990, pp. 7–36.

Dubatolov, V.N., Yuferev, O.V., Zadorozhnyi, V.M., *et al.*, TITLE, in *Paleozoi yugo-vostoka Zapadno-Sibirskoi plity* (Paleozoic in the Southeast of the West Siberian Platform), Novosibirsk: Nauka, 1984, pp. 74–135

Gratsianova, R.T., Brachiopods, in *Paleozoi yugo-vostoka Zapadno-Sibirskoi plity* (Paleozoic in the Southeast of the West Siberian Platform), Novosibirsk: Nauka, 1984, pp. 136–140.

Gratsianova, R.T., Middle Paleozoic Paleogeography in the South of the West Siberian Platform, in *Geologiya nefte- i uglenosnykh oblastei Sibiri* (Geology of Oil and Coal Bearing Fields in Siberia), Novosibirsk: Nauka, 1985, pp. 73–95.

Isaev, G.D., Krasnov, V.I., Aksenova, L.M., *et al.*, Discovery of the Ordovician in the Nyurol' Structural Region (Middle Courses of the Ob River), in *Stratigrafiya i paleontologiya dokembriya i fanerozoya Sibiri* (Precambrian and Phenerozoic Stratigraphy and Paleontology of Siberia), Novosibirsk: Nauka, 1990, pp. 1–17.

Isaev, G.D., Saev, V.I., Peregoedov, L.G., *et al.*, Kyshtovka and Armichevka Horizons of Devonian in the Southeast of the West Siberian Platform, in *Aktual'nye problemy regional'noi geologii Sibiri (stratigrafiya, tektonika, paleogeografiya, mineralogiya)* (Urgent Problems of Regional Geology in Siberia), Novosibirsk: Nauka, 1992a, pp. 48–49.

Isaev, G.D., Saev, V.I., Krasnov, V.I., *et al.*, Biostratigraphy of the Emsian Deposits in the Southeast of the West Siberian Platform, in *Materialy po paleontologii i stratigrafii Zapadnoi Sibiri* (Data on Paleontology and Stratigraphy of the Western Siberia), Tomsk: Tomsk. Univ., 1992b, pp. 15–35.

Krasnov, V.I., Stepanov, S.A., Isaev, G.D., *et al.*, Local Stratigraphic Units of the Middle Paleozoic in the Southeast of the West Siberian Platform, *Aktual'nye voprosy geologii Sibiri* (Urgent Problems of Geology in Siberia), Tomsk: Tomsk. Univ., 1988, vol. 1, pp. 81–84.

Krasnov, V.I., Stepanov, S.A., Ratanov, L.S., *et al.*, Local Stratigraphic Units of the Middle Paleozoic for Geological Survey and Prospecting in the Western Siberia, in *Regional'nye i mestnye stratigraficheskie podrazdeleniya dlya krupnomasshtabnogo geologicheskogo kartirovaniya Sibiri* (Regional and Local Stratigraphic Subdivisions for the Large-Scale Geological Survey in Siberia), Novosibirsk: Nauka, 1986, pp. 58–65.

Kul'kov, N.P., The Llandoverian Brachiopod *Virgianella* Nikiforova et Sapelnikov, 1971, from the Southwest of the West Siberian Platform, *Geol. Geofiz.*, 1991, no. 11, pp. 107–110.

Kul'kov, N.P. and Ivanovskii, A.B., Silurian Stratigraphic Subdivisions, *Geol. Geofiz.*, 1978, no. 9, pp. 23–30.

Kul'kov, N.P. and Matukhin, R.G., Correlation of the Lower Devonian Deposits in Siberian and the West Siberian Platforms, *Geol. Geofiz.*, 1990, no. 10, pp. 115–117.

Kul'kov, N.P. and Peregoedov, L.G., Stratigraphy of the Lower Devonian Deposits in the West Siberian Platform as Indicated by Data on Brachiopods, *Geol. Geofiz.*, 1989, no. 1, pp. 3–13.

Kul'kov, N.P. and Peregoedov, L.G., Substantiation of the Eifelian Stage in the Southeast of the West Siberian Platform, *Geol. Geofiz.*, 1993, no. 5, pp. 3–9.

Kul'kov, N.P., Krasnov, V.I., Peregoedov, L.G., *et al.*, The Lower Carboniferous in the North of the West Siberian Plain, *Geol. Geofiz.*, 1991, no. 10, pp. 49–54.

Modzalevskaya, T.L., Silurian Brechiopods from New Zealand and Their Significance for Correlation, in *Stratigrafiya i paleontologiya paleozoya Sovetskoi Arktiki* (Paleozoic Stratigraphy and Paleontology in the Soviet Arctic Regions), Leningrad: Vses. Geol. Inst., 1989, pp. 58–76.

Nikiforova, O.I., Brachiopods from the Grebenka Horizon of the Vaigach Island (Late Silurian), in *Stratigrafiya i fauna siluriiskikh otlozhenii Vaigacha* (Stratigraphy and Fauna from Silurian Deposits of the Vaigach Island), Leningrad: Nauka, 1970, pp. 97–149.

Peregoedov, L.G., Results of Ecologic-Taphonomic Analysis of Brachiopods from Well Maloichskaya-7, in *Paleoekologicheskii i litologo-fatsial'nyi analizy dlya obosnovaniya detal'nosti regional'nykh stratigraficheskikh skhem* (Paleoecologic and Lithologic Analyses Aimed to Substantiate Regional Stratigraphic Schemes), Novosibirsk: Nauka, 1986, pp. 100–105.

Peregoedov, L.G., Some Eifelian Brachiopods from Well Malaya Icha-7, in *Silur i devon yugo-vostoka Zapadno-Sibirskoi plity* (Silurian and Devonian in the Southeast of the West Siberian Platform), Moscow: Nauka, 1990, pp. 78–90.

Saev, V.I., Biostratigraphy of the Lower–Middle Devonian of the West Siberian Platform as Implied by Data on Foraminifers, in *Geologiya pozdnego dokembriya i paleozoya Sibiri* (Geology of the Late Precambrian in Siberia), Novosibirsk: Siberian Research Inst. Geol. Geochem. Mineral Resources, 1990, pp. 102–103.

Saev, V.I., Biostratigraphy of the Lower–Middle Devonian Based on Foraminiferes, in *Materialy po paleontologii i stratigrafii Zapadnoi Sibiri* (Data on Paleontology and Stratigraphy of the Western Siberia), Tomsk: Tomsk. Univ., 1992, pp. 36–42

Saev, V.I., Makarenko, S.N., Isaev, G.D., *et al.*, The Gerasimivo Horizon of the Middle Devonian in the Southeast of the West Siberian Platform, in *Aktual'nye problemy regional'noi geologii Sibiri (stratigrafiya, tektonika, paleogeografiya, mineralogiya* (Urgent Problems of Regional Geology in Siberia: Stratigraphy, Tectonics, Paleogeography, and Mineralogy), Novosibirsk: Siberian Research Inst. Geol. Geochem. Mineral Resources, 1992, p. 50.

Saev, V.I., Savina, N.I., and Tat'yanin, G.M., Some Trends in Geological Evolution of the Northern Ostanino Area during the Paleozoic (the Southeast of the West Siberian Platform), in *Materialy po stratigrafii i paleontologii Sibiri* (Data on Paleontology and Stratigraphy of Siberia), Tomsk: Tomsk. Univ. 1987, pp. 3–10.

Saev, V.I., Savina, N.I., Miretskaya, N.M., *et al.*, Stratigraphy of the Lower Devonian in the Southeast of the West Siberian Platform: New Data on Foraminifers, Ostracodes, Conodonts, and Tentaculites, in *Geologiya pozdnego dokembriya i paleozoya Sibiri* (Geology of the Late Precambrian and Paleozoic in Siberia), Novosibirsk: Siberian Research Inst. Geol. Geochem. Mineral Resources, 1990, pp. 97–99.

Saev, V.I., Savina, N.I., Tat'yanin, G.M., *et al.*, Devonian Stratigraphy in the Western Ostanino Area (the Southeast of the West Siberian Platform), in *Materialy po paleontologii i stratigrafii Zapadnoi Sibiri*, (Data on Paleontology and Stratigraphy of the Western Siberia), Tomsk: Tomsk. Univ. 1988, pp. 10–19.

Savina, N.I., Devonian Ostracodes from the West Siberian Platform and Their Stratigraphic Significance, *Cand. Sci. (Geol.-Mineral.) Dissertation,* Novosibirsk: Siberian Research Inst. Geol. Geochem. Mineral Resources, 1993.

Silur i devon yugo-vostoka Zapadno-Sibirskoi plity (Silurian and Devonian in the Southeast of the West Siberian Platform), Moscow: Nauka, 1990.

Stepanov, S.A., Krasnov, V.I., Kul'kov, N.P., *et al.,* Geological Section of the Parametric Well Maizas-1 (Ludlow–Early Devonian, Western Siberia), in *Biostratigrafiya i biogeografiya paleozoya Sibiri* (Biostratigraphy and Biogeography of the Paleozoic in Siberia), Novosibirsk: Nauka, 1985, pp. 64–76.

Stratigrafiya paleozoiskikh otlozhenii yugo-vostoka Zapadno-Sibirskoi plity (Stratigraphy of Paleozoic Deposits in the Southeast of the West Siberian Platform), Novosibirsk: Nauka, 1990.

Zadorozhnyi, V.M., *Foraminifery i biostratigrafiya devona Zapadno-Sibirskoi plity i ee skladchatogo obramleniya* (Devonian Foraminifers and Biostratigraphy of the West Siberian Platform and Its Folded Framing), Novosibirsk: Nauka, 1987.

Stratigraphy and Geological Correlation, Vol. 5, No. 6, 1997, pp. 561–571. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 5, No. 6, 1997, pp. 40–50.
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Paleogene Planktonic Foraminifers and Stratigraphy of the Obruchev Rise (Northern Pacific)

I. A. Basov

Institute of the Lithosphere, Russian Academy of Sciences, Staromonetnyi per. 22, Moscow, 109180 Russia

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Abstract—The taxonomic composition of planktonic foraminifers from the relatively complete Paleogene sections first recovered by deep-sea drilling in high latitudes of the North Pacific allowed these deposits to be dated and subdivided. In its composition and morphological peculiarities, the Paleogene assemblage of planktonic foraminifers from the Obruchev Rise is similar to that from coeval deposits in high-latitude areas of the Earth: the Crimea–Caucasus and Koryak–Kamchatka regions in the northern hemisphere, and from the Campbell, Kerguelen, and Falkland plateaus and New Zealand in the southern hemisphere. Based on the distribution of the planktonic foraminiferas, only major stratigraphic units of the subseries rank can be distinguished in the Paleogene section of the Obruchev Rise, whereas the lower Eocene interval can be subdivided into zonal units of the Crimea–Caucasus biostratigraphic scale. Changes in the foraminifera composition generally reflect global climatic fluctuations inferred worldwide by paleontologic and isotopic studies.

Key words: *Paleogene, planktonic foraminifers, species diversity, biostratigraphy, climate, Obruchev Rise, Pacific.*

INTRODUCTION

The study of Paleogene deposits in the high-latitude areas of the North Pacific is of extreme importance, because their sections record many geological events, which largely controlled the paleooceanologic and climatic evolution and development of biota both in this region and the entire Pacific.

Although samples of the sedimentary cover of the Pacific have been recovered by thousands of holes, Paleogene sediments in the high-latitudes of the North Pacific were virtually unknown until recently. Paleogene deposits had been drilled here only at DSDP Site 192 (Leg 19 of *Glomar Challenger*) on the Meiji Guayot more than 20 years ago. This hole penetrated 90-m-thick Eocene–Oligocene carbonate–clayey sediments containing an impoverished, poorly preserved assemblage of planktonic foraminifers and unconformably overlying the upper Maastrichtian deposits of the *Abathomphalus mayaroensis* Zone (Creager *et al.*, 1973). Hole 192 was drilled with spot coring, which affected the stratigraphic resolution and significantly reduced chances for discovery of calcareous microfossils.

During Leg 145 JOIDES Resolution of the Ocean Drilling Program, relatively complete Paleogene sections with sufficiently diverse and, in general, satisfactorily preserved planktonic foraminifers were first recovered in the high latitudes of the North Pacific (Rea *et al.*, 1993). They were drilled at two sites (883 and 884) on the submarine Obruchev Rise representing the northern extremity of the Emperor Seamount chain that stretches in the submeridional direction from approximately 30° N in the south, where it joins the Hawaiian Ridge, to 52° N in the north. Holes were drilled on top of the Obruchev Rise and at the foot of its eastern slope, respectively. (Fig. 1).

The different bathymetric position of the sites is responsible for the different patterns of the recovered Paleogene sections and planktonic foraminifera assemblages incorporated in them.

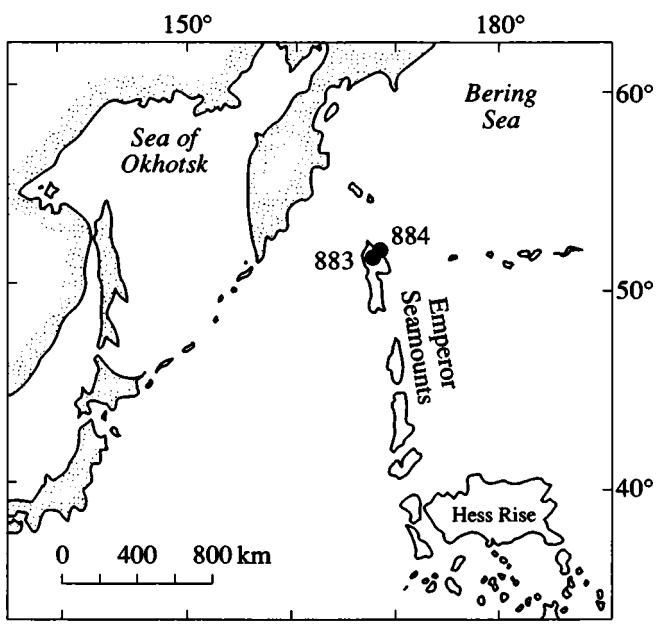

Fig. 1. Location of studied sections.

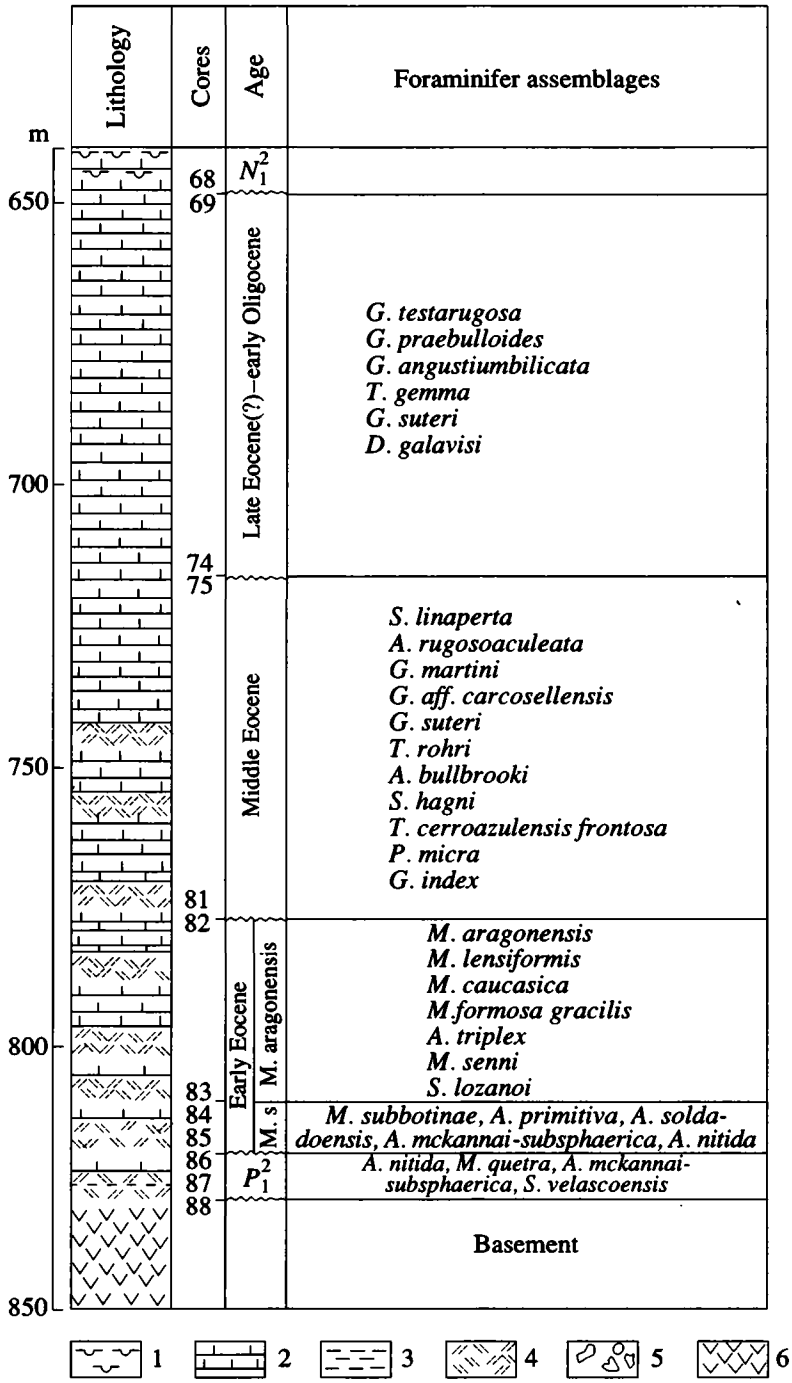

Fig. 2. Lithology and stratigraphy of Paleogene deposits at the ODP Site 883.
(1) Diatom ooze; (2) chalk; (3) clay; (4) volcanic ash; (5) syngenetic breccia; (6) basalt.

At Site 883 (51°11.908′ N; 167°46.128′ E; water depth of 2385 m), the Paleogene section 177.8 m thick (interval of 652.2–830 m) is mainly composed of nannofossil chalk with subordinate interbeds of volcanic ash (Fig. 2). The number and thickness of ash interbeds increases upsection. In basal Paleogene layers, volcanic ash becomes the dominant component of sediments. The calcium carbonate content in the upper part of the section varies from 38.8 to 96%. In the lower part of the section, its content is lower because of the increased amount of volcanic ash, which is often transformed into clay, and varies from 2.8 to 86.9%. Sediments in the lower part of the section display structures of underwater slumping and gravitational reworking. This is also evident from the presence of diamictite and turbidite interbeds. Deposition in this area occurred in the lower

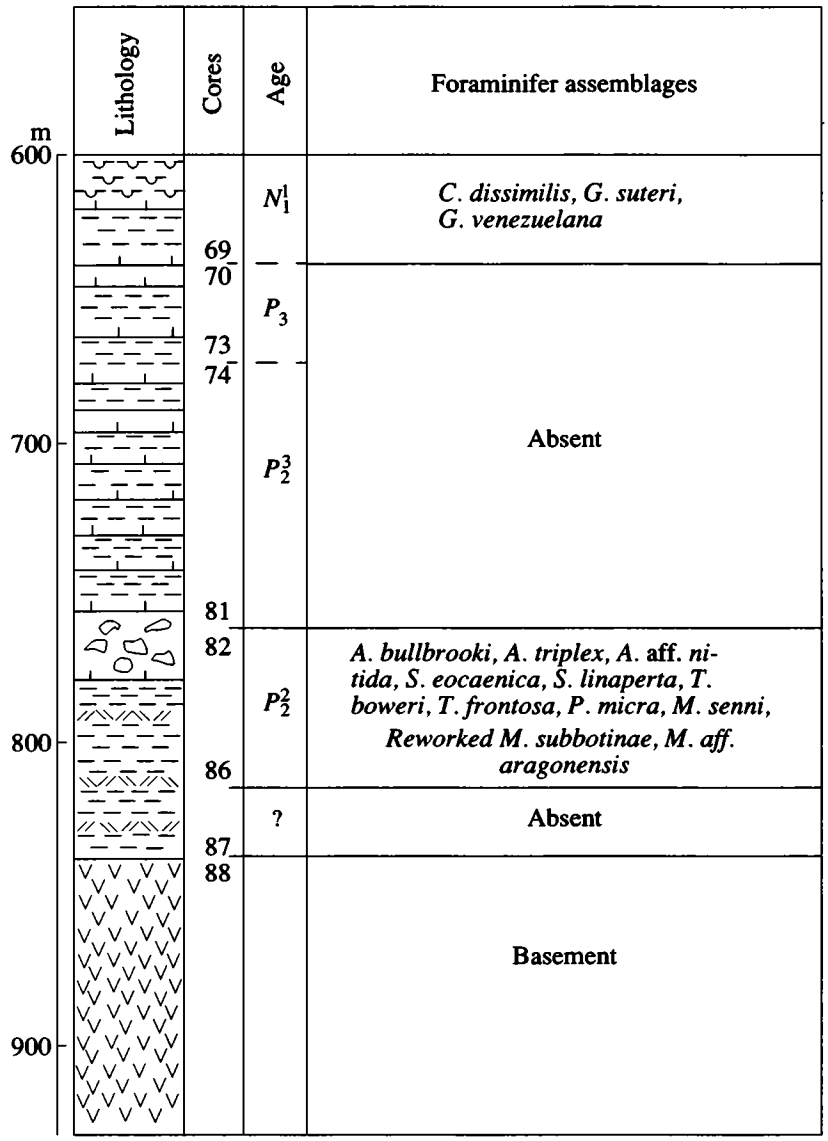

Fig. 3. Lithology and stratigraphy of Paleogene deposits at the ODP Site 884 (symbols as in Fig. 2).

bathyal environments at the depth of 1800–2000 m (Rea *et al.*, 1993, 1995a).

At the deeper Site 884 (51°27.026′ N; 168°20.228′ E; water depth of 3826 m), the Paleogene section with the total thickness of 190 m (interval of 664–854 m) is mainly composed of siltstones with rare interbeds of nannofossil chalk in its lower and upper parts (Fig. 3). The middle part of the section is represented by irregular interbedding of a similar chalk, siltstone (probably, altered volcanic ash), and relatively fresh volcanic ash. The upper two-thirds of the section show various signs of sediment reworking downslope: syngenetic deformation, including convolute lamination, microfaulting, and load clasts. The wide development of these processes is evident from the presence of diamictite conglomerate horizons (up to 1 m thick) composed of syngenetically deformed angular fragments of siltstone, altered volcanic ash, and chalk, all incorporated in the matrix of the same lithology. According to the expedition participants (Rea *et al.*, 1993, 1995a), the section was formed at the depth of 3000–3500 m.

Paleogene deposits drilled at both sites overlie a basaltic basement of the Late Cretaceous age and, in turn, are unconformably overlain by lower Miocene sediments.

MATERIALS AND METHODS

Both sites were drilled using the advanced technology of core sampling. This allowed the section to be almost continuously sampled.

Samples for foraminiferal studies were collected from each 1.5-m core section, as well as from all the core catchers. In total, 69 and 110 samples were taken

from Sites 883 and 884, respectively. Samples were mainly collected from calcareous sediments, preferably from layers with no or slight disturbance or reworking of sedimentary material by downslope processes, or from lithified rock fragments of the drilling breccia. The samples taken at Site 883 had a volume of 10 cm^3, whereas 20-cm^3 samples were collected from Site 884.

All the samples were treated according to traditional methods and washed through a 63-μm sieve. Dried residues were then examined with a light microscope to determine the abundance, preservation, and composition of foraminifers.

RESULTS

Planktonic foraminifers occur in Paleogene sediments penetrated at both sites (Basov, 1995). They are most abundant and diverse and are better preserved at the shallower Site 883 drilled at the top of the Obruchev Rise. Out of the five holes drilled at this site, Hole 883B provided the most complete and well-sampled Paleogene section. Therefore, the main attention will be paid to the analysis of the composition and stratigraphic distribution of planktonic foraminifers from this hole.

Planktonic foraminifers in Hole 883 occur throughout the Paleogene sequence but significantly vary in abundance and degree of preservation (Fig. 4). In general, the relatively abundant and diverse assemblages of planktonic foraminifers are better preserved, and, on the contrary, the impoverished assemblages are poorly preserved.

On the whole, the planktonic foraminifer assemblages at Site 883 are impoverished, as compared with those in coeval sediments from more southern areas of the North Pacific (for instance, in the Hess and Schatsky rises area). Their low diversity and poor preservation in general, as well as the absence of many zonal species, make the precise dating and reliable subdivision of certain intervals difficult. This is particularly true of the basal and upper parts of the Paleogene section, where the foraminiferal assemblage is of a minimal diversity and poorly preserved. Because of these features, only major stratigraphic units of the series or subseries rank can be defined in the section; the zonal units are recognizable only in the lower Eocene interval.

The upper Paleocene. Sediments from the basal part of the sedimentary section (Cores 86 and 87; depth interval of 818–837 m) overlying the basaltic basement were arbitrarily ascribed to the upper Paleocene. Only samples from Core 86 were available for this study. Sediments from this core contain single specimens of *Acarinina mckannai, A. nitida, Subbotina velascoensis, S.* sp., and *Morozovella quetra*, which allows the host sediments to be dated as late Paleocene in age (the interval of *Morozovella pusilla* to *Morozovella velascoensis* zones of the Caribbean foraminiferal scale). Data on nannofossil distribution contradict this conclusion. In preparations from this core, as well as from sediments filling fissures in the basaltic basement, an impoverished nannoplankton assemblage of the Late Cretaceous (late Maastrichtian?) was identified (Beaufort and Olafsson, 1995).

In one of the studied samples from Core 86, I also found two foraminiferal shells of the late Maastrichtian species *Abathomphalus mayaroensis*. Nonetheless, the presence of single late Paleocene *Acarinina* and *Morozovella* in the same and two other samples collected lower in the section most likely suggests redeposition of the former. However, downhole contamination also can not be ruled out.

Only sediments from the interval of 814–818 m (Core 85) were referred to the upper Paleocene on the basis of nannoplankton. These sediments yielded a nannofossil assemblage that correlates them with the NP9 Zone (Beaufort and Olafsson, 1995). This core was not sampled for the foraminiferal studies, because the Paleocene–Eocene boundary appears to be inside its interval. As became known recently, this boundary is marked by major abiotic and biotic events attracting the attention of many researchers. Therefore, because of the limited material, special permission of the Ocean Drilling Program administration is needed for sampling the boundary layers.

The lower Eocene. Lower Eocene deposits were defined in the interval of 779.2–814 m (Cores 82–85). According to the nannofossils, all but the basal NP10 Zone of the lower Eocene were identified there (Beaufort and Olafsson, 1995). The NP11 Zone corresponding to the interval of *Morozovella subbotinae* and *Morozovella formosa formosa* foraminiferal zones of the Caribbean scale (Berggren *et al.*, 1985) was recognized in the basal 1-m-thick bed of the lower Eocene (the middle part of Core 85), from which samples for foraminiferal studies were not collected for the abovementioned reasons. The most part of the lower Eocene section was referred to the NP12 Zone, which corresponds to the uppermost part of the *Morozovella formosa formosa* Zone and a greater part of the *Morozovella aragonensis* Zone of the tropical–subtropical foraminiferal scale (Berggren *et al.*, 1985). Two samples from the uppermost lower Eocene sediments (uppermost 1.5 m) yielded a nannoplankton assemblage correlative with the NP13 Zone (Beaufort and Olafsson, 1995). The latter corresponds to the upper part of the *Morozovella aragonensis* Zone and the *Acarinina pentacamerata* Zone of the terminal lower Eocene.

Thus, according to the nannofossil data, almost the whole lower Eocene part of the section, except for its basal and top layers, belongs to the *Morozovella aragonensis* Zone of the Caribbean foraminiferal scale. The absence of nannofossils characteristic of the NP10 Zone and representing the main part of the NP11 Zone indicates a stratigraphic gap between the Paleocene and Eocene sediments.

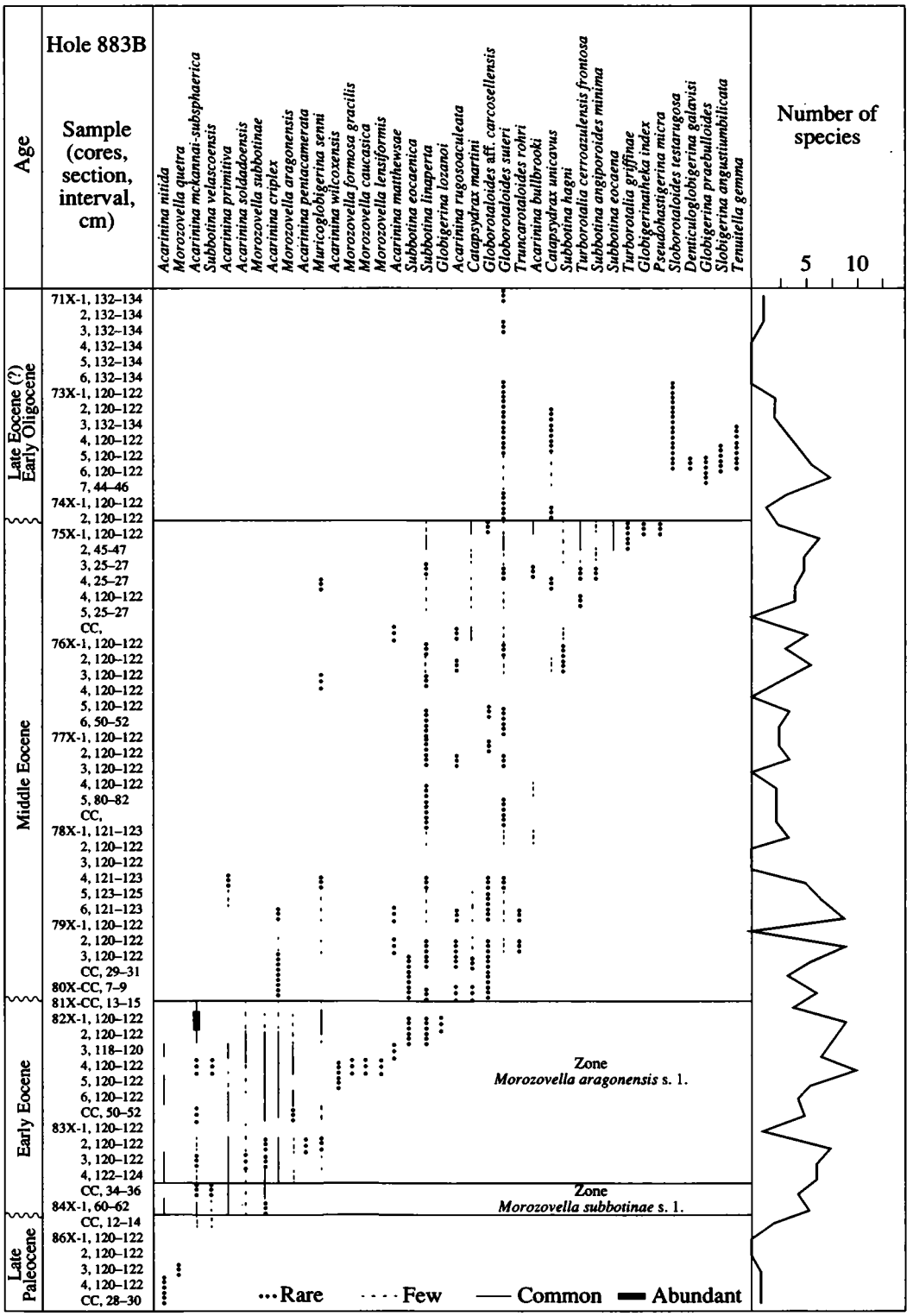

Fig. 4. Stratigraphic distribution and diversity of planktonic foraminifers in Paleogene sediments of the ODP Site 883.

However, a thorough consideration of data on the nannoplankton distribution in the lowermost Eocene of Holes 883B and 883E (Cores 85 and 19, respectively) published by the above-mentioned authors reveals that they contradict drilling results. According to core sampling data, the interval of Core 19 (Hole 883E; depth interval of 807.5–817.4 m), the upper part of which yielded the nannoplankton assemblage of the NP7 and

NP8 zones, corresponds to the interval of Core 85 (Hole 883B; depth interval of 808.9–818.5 m) referred to the NP12 Zone. This may indicate that the nannoplankton assemblage of this later zone could have been reworked and redeposited into younger sediments. This is highly probable if we take into account the hiatus at the Paleocene–Eocene boundary.

Planktonic foraminifers in the lower Eocene sediments (Cores 82–84) display a relatively high diversity and are generally well preserved. Their diversity amounts to 20 species. The most common among them are *Acarinina nitida, A. mckannai-subsphaerica* group, *A. primitiva, A. soldadoensis, A. triplex, Morozovella subbotinae, M. aragonensis,* and *Muricoglobigerina senni.* Less common are *Subbotina velascoensis, S. eocaenica, S. linaperta, S. lozanoi, Acarinina pentacamerata, A. wilcoxensis, A. matthewsae, Morozovella caucasica, M. formosa gracilis,* and *M. lensiformis.*

This assemblage allows me to date reliably the host sediments as early Eocene in age and outline their zonal subdivision. At the same time, as is evident from the analysis of its composition and species distribution through the section, the standard tropical–subtropical zonation (Bolli, 1957a, 1957b, 1957c, 1966; Blow, 1969) and its later modifications (Bolli and Premoli Silva, 1973; Premoli Silva and Bolli, 1973; Berggren *et al.,* 1985; Toumarkine and Luterbacher, 1985; and others) appear to be inapplicable in this case. The most suitable scale here is the Crimea–Caucasus zonal scale (Krasheninnikov, 1980), which was previously applied in the subdivision of Paleogene sections of the Pacific high-latitudes (Krasheninnikov *et al.,* 1988; Krasheninnikov *et al.,* 1992).

According to this biostratigraphic scale, sediments from the lower part of the lower Eocene section (Core 84) containing *Morozovella subbotinae, Subbotina velascoensis, Acarinina mckannai-subsphaerica, A. primitiva, A. soldadoensis,* and *A. nitida* can be correlated with the *Globorotalia* (=*Morozovella*) *subbotinae* s.l. Zone, which was established in Paleogene deposits of the high-latitude areas of the Pacific (Krasheninnikov *et al.,* 1988). In the tropical–subtropical (Caribbean) zonal scale (Premoli Silva and Bolli, 1973), this zone corresponds to the interval of *Morozovella edgari, Morozovella subbotinae* s. str, and *Morozovella formosa formosa* zones, whereas in the Crimea–Caucasus scale it spans the interval of *Morozovella subbotinae* s. str.–*Morozovella marginodentata* zones.

Sediments from the upper, larger, part of the lower Eocene section are correlative, based on planktonic foraminifers, with the *Morozovella aragonensis* s. l. Zone, which corresponds to the interval of *Morozovella aragonensis* s. str. and *Morozovella palmerae* zones in the Caribbean zonal scale (Premoli Silva and Bolli, 1973). The boundary between the *Morozovella subbotinae* s. l. and *Morozovella aragonensis* s. l. zones is at the base of Core 83 (the depth of 799.2 m) directly below the first occurrence of the index species of the latter zone. In the Pacific, the appearance of this species marks the base of the *Morozovella aragonensis* Zone (Krasheninnikov, 1982; Krasheninnikov *et al.,* 1988), though some researchers (Toumarkine and Luterbacher, 1985) reported it from a slightly lower level (the *Morozovella formosa formosa* Zone). Judging from the presence of relatively numerous specimens of *Morozovella subbotinae* in the top layers of the lower Eocene interval, sediments of the *Morozovella palmerae* Zone [=*Acarinina pentacamerata* Zone in the scale of Toumarkine and Luterbacher (1985)] of the terminal lower Eocene are most likely missing here. Probably, the latter zone is represented here by its basal layers. According to different data (Krasheninnikov, 1982; Toumarkine and Luterbacher, 1985; Krasheninnikov *et al.,* 1988), *Morozovella subbotinae* became extinct at the top of the *Morozovella aragonensis* s. str. Zone.

Thus, according to the planktonic foraminifer distribution, the lower Eocene sediments in the Obruchev Rise area are separated from both underlying and overlying deposits by stratigraphic gaps, as is also evidenced by nannofossil data.

The middle Eocene. The middle Eocene sediments were established in the depth interval of 712.6–779.2 m (Cores 75–81). According to the nannofossils, these sediments incorporate the whole succession of the middle Eocene zones (Beaufort and Olafsson, 1995): from the NP14 Zone (probably, without its lower part) to the NP16 Zone (most likely without its upper part).

Planktonic foraminifers from the middle Eocene sediments are characterized by a low abundance, irregular distribution, and, in general, poor preservation. Nonetheless, their assemblage is comparable in its diversity with that from the lower Eocene strata (Fig. 3). In the lower part of the middle Eocene section, the assemblage includes the first appearing species *Acarinina rugosoaculeata, Subbotina linaperta, Catapsydrax martini, Globorotaloides suteri,* and *G. carcosellensis* along with species passing into this level from the lower Eocene sediments, such as *Acarinina triplex, A. primitiva,* and *Muricoglobigerina senni.* The lower part of the section yielded only rare *Subbotina linaperta, Acarinina rugosoaculeata, A. bullbrooki, Globorotaloides suteri,* and *G. carcosellensis.* A relatively diverse assemblage (14 species in total) is present in the upper portion of the middle Eocene section, where I identified *Subbotina eocaena, S. linaperta, S. hagni, S. angiporoides minima, Turborotalia cerroazulensis frontosa, T. griffinae, Globigerinatheca index, Catapsydrax martini, Globorotaloides suteri, Pseudohastigerina micra,* and others.

The above-listed foraminiferal assemblage unambiguously correlates the host sediments with the middle Eocene. At the same time, it remains unclear what part of the middle Eocene is present in this section. The occurrence of certain species in the lower layers, such as *Acarinina rugosoaculeata, Subbotina linaperta, Globorotaloides suteri,* and *Catapsydrax*

martini, may indicate that only the upper middle Eocene sediments are present here. Nevertheless, considering the poor preservation of foraminifers and their specific characteristics (small dimensions, compact arrangement of chambers, less open aperture, and others) that make identification difficult, one can not exclude the presence of the lower middle Eocene in this section. Data on nannofossils (Beaufort and Olafsson, 1995) imply that sediments of the lower part of the NP14 Zone (the NP14a Subzone) of the basal middle Eocence are most likely missing, and this in combination with the insignificant thickness of sediments containing the assemblage of the NP13 Zone of the terminal lower Eocene favors the presence of a hiatus at the lower–middle Eocene boundary. As mentioned above, this hiatus is also inferred from data on foraminifer distribution.

The upper Eocene (?)–Oligocene. Sediments of this age were recovered in the interval of 664.4–712.6 m (Cores 69–74). According to the nannofossils, they are correlated with the NP22 Zone of the lower Oligocene (Beaufort and Olafsson, 1995); i.e., they overlie the middle Eocene deposits with stratigraphic unconformity.

In this interval, planktonic foraminifers occur only in sediments from Cores 71–74, which yielded an impoverished poorly preserved assemblage of seven species. The most common here are *Globorotaloides suteri, G. testarugosa,* and *Catapsydrax unicavus. Globigerina praebulloides, G. angustiumbilicata,* and *Tenuitella gemma* occur in separate samples. The occurrence of the latter species in Core 73 indicates the early Oligocene age of the host sediments, though the presence of upper Eocene strata cannot be completely ruled out.

Sediments directly overlying the lower Oligocene strata (Cores 69–70) are arbitrarily referred to the upper Oligocene based on the presence of the diatom species *Cavitatus miocenica* (Barron and Gladenkov, 1995). The first occurrence level of this form is dated back to 30.6 Ma according to the paleomagnetic scale (Cande and Kent, 1992).The presence of upper Oligocene sediments in the section under consideration, or close to it in the Obruchev Rise, is indirectly confirmed by single finds of reworked Oligocene planktonic foraminifers *Globigerina tripartita* and *G. ciperoensis* in the basal layers of the lower Miocene (Core 68). The latter species is a zonal form of the upper Oligocene *Globigerina ciperoensis* Zone. Simultaneously, no other data suggest the presence of upper Oligocene sediments in this section; therefore, it is not inconceivable that sediments of the considered interval are early Miocene in age. In this case, the hiatus at the Oligocene–Miocene boundary, evident from the distribution of all microfossil groups, diatoms included, spans the late Oligocene (probably its second half) and the earliest Miocene.

The basal layers of the lower Miocene at Site 883 correlative with the diatom *Thalassiosira spinosa* Zone (Barron *et al.*, 1995) yield an impoverished assemblage of planktonic foraminifers consisting of *Catapsydrax dissimilis, C. martini, Globigerina venezuelana,* and rare *Globorotaloides suteri, G. testarugosa, Globigerina euapertura,* and *G. praebulloides.*

At Site 884, Paleogene sediments were recovered in the depth interval of 642–815 m (Cores 70–87). According to the nannofossils, the lower part of the Paleogene section is correlated with NP14–NP16 zones of the middle Eocene (Olafsson and Beaufort, 1995). Sediments from the upper portion of this interval contain an impoverished poorly preserved nannoplankton assemblage that allows the sediments to be referred to the lower Oligocene (the NP22 Zone). Nannofossils of the early and middle Eocene are also common here and suggest an intense reworking of deposits.

Planktonic foraminifers in Paleogene sediments recovered at Site 884 are of low diversity and abundance; they are poorly preserved and show an extremely irregular distribution through the section. Among the 145 samples collected from the Paleogene sediments for foraminiferal analysis, only 23, mainly from the lower portion of the section (Cores 82–84), yielded planktonic foraminifers. This assemblage mainly consists of *Acarinina primitiva, A. bullbrooki, Subbotina linaperta, S. eocaena, Muricoglobigerina senni,* and *Turborotalia cerroazulensis frontosa.* Less common are *Acarinina pentacamerata, A. triplex, Subbotina eocaenica, Turborotalia boweri,* and *Pseudohastigerina micra.* This assemblage allows the host sediments to be dated as middle Eocene (most probably, late middle Eocene) in age.

Sediments from the lower portion of the section also contain reworked poorly preserved shells of the early Eocene forms *Morozovella* aff. *subbotinae* and *Acarinina* aff. *nitida.* Rare poorly preserved specimens of the early-middle Eocene form *Morozovella* aff. *aragonensis* found here are also most likely redeposited.

DISCUSSION

Paleogene sections with relatively diverse calcareous microfossils, which allowed the host sediments to be dated and subdivided (Barron *et al.*, 1995), were first penetrated by drilling in the high-latitude North Pacific (the Obruchev Rise) during Leg 145 of the Ocean Drilling Program. A relatively complete Paleogene section was recovered at the top of the rise (Site 883), where it is underlain and overlain with stratigraphic unconformities by the Upper Cretaceous (upper Maastrichtian) and Neogene (lower Miocene) deposits.

The Paleogene assemblage of planktonic foraminifers from this section is of a higher diversity (approximately 40 species) and, generally, better preserved, as compared with that from the deeper Site 884. Based on changes in the composition of foraminifers, the upper Paleocene, lower Eocene, middle Eocene, and Oligocene intervals are distinguished at Site 883. At Site 884, the impoverished (about 10 species) and poorly preserved foraminiferal assemblage from sediments of the middle

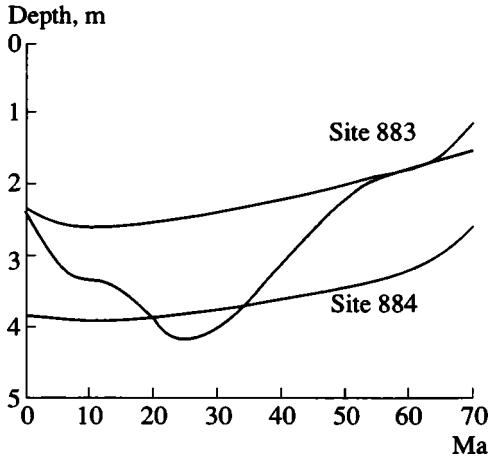

Fig. 5. Paleodepths and calcium carbonate compensation depth in the Obruchev Rise area in the Cenozoic (after Rea *et al.*, 1995).

portion of the Paleogene section allowed them to be dated as middle Eocene in age.

Planktonic foraminifers from both sections have, as a rule, small compact shells with muted surface ornamentation and restricted apertures or with a weakly developed apertural lip. These morphological peculiarities, usually characteristic of planktonic foraminifer species from high latitudes (Krasheninnikov *et al.*, 1988; Basov, 1995) and distinguishing them from foraminiferal species of lower latitudes, make species identification difficult in many cases. The planktonic foraminifer assemblages from Paleogene sediments of the Obruchev Rise reveal features that make them similar to assemblages from the high-latitude areas. Most common are representatives of *Subbotina* and *Acarinina* genera; only in the lower Eocene interval do keeled morozovellids occur in noticeable amounts. Worth mentioning is the absence of many species of such genera as *Hantkenina, Globigerinatheca, Truncatulinoides,* and *Orbulinoides,* along with many keeled and conical morozovellids, which are common in Paleogene sediments at lower latitudes, for instance, in the Schatsky and Hess rises, Mid-Pacific Seamounts, and other regions (Krasheninnikov and Hoskins, 1973; Krasheninnikov, 1982).

Similar planktonic assemblages dominated by species of the *Acarinina* and *Subbotina* genera were reported from coeval sediments in many high-latitude areas of the southern hemisphere: New Zealand (Jenkins, 1971), Campbell Plateau (Jenkins, 1975; Jenkins and Srinivasan, 1985; Krasheninnikov *et al.*, 1988), Kerguelen Plateau (Huber, 1991; Berggren, 1992), Falkland Plateau (Tjalsma, 1977; Krasheninnikov and Basov, 1986), and Maud Rise (Stott and Kennett, 1990). Assemblages of this type were also described from the southern areas of the former Soviet Union (Subbotina, 1953; Shutskaya, 1970), in particular from the Koryak–Kamchatka region (Krasheninnikov *et al.*, 1988).

According to the plate-tectonics reconstructions, all the listed areas were located in the Paleogene at the higher latitudes, as compared with the Obruchev Rise. The position of the rise at the beginning of the Oligocene (35 Ma) was estimated by the participants of the Oceanic Drilling Program Leg 145 to be approximately at 40°N (Rea *et al.*, 1995), i.e., almost throughout the Paleogene it was situated within the subtropical realm. This inference allows us to assume that the taxonomic impoverishment of Paleogene planktonic foraminifers in the Obruchev Rise area was sooner related to the influence of selective dissolution rather than to their initial low diversity. This assumption is supported by the low degree of preservation of foraminiferal shells, whose diversity and abundance depend on this factor. As a rule, the more diverse the foraminifers are more abundant and better preserved, and vice versa.

Materials of Leg 145 show that the calcium carbonate compensation depth (CCD) in the Obruchev Rise area experienced significant fluctuations in the Paleogene (Rea *et al.*, 1995b). At the beginning of the Paleogene, the CCD level was probably at depths of about 2000 m. During the Eocene, it was at the depth of 2500–3000 m; it then lowered to 3700–3800 m by the beginning of the Oligocene and remained at this level until the Neogene. Beginning in the early Miocene, the CCD constantly rose to its modern level with a sharp acceleration in the Quaternary time (Fig. 5). Thus, sedimentation on the top of the Obruchev Rise near Site 883 occurred above the CCD level during almost all of the Eocene and in the Oligocene. As a result, a sequence of nannofossil chalk was deposited. At the same time, poor preservation of both planktonic foraminifers and nannofossil assemblages suggests that deposition occurred at the depth separating foraminiferal and nannoplankton lysoclines, most probably close to the latter.

The impoverished composition of planktonic foraminifers from the Paleogene sediments of the Obruchev Rise hinders the detailed subdivision of the section. With the help of planktonic foraminifers, we may distinguish here only major stratigraphic units of the subseries rank; lower stratigraphic units are recognizable only in the lower Eocene. This interval can be subdivided into lower and upper parts correlated with the *Morozovella subbotinae* s. l. and *Morozovella aragonensis* s.l. zones, respectively, of the Crimea–Caucasus foraminiferal scale (Krasheninnikov, 1980), the first of which corresponds to three and the second of which corresponds to two zones of the tropical–subtropical scheme. The application here of the foraminiferal scale suggested for the Paleogene sediments of the Antarctic region (Stott and Kennett, 1990) faces significant obstacles, because many zonal species, such as *Planorotalites ausraliformis, Acarinina pentacamerata, Chiloguembelina cubensis, Pseudohastigerina*

micra, and *Globigerinatheca index* are absent or show discrete distribution in the studied area.

The analysis of planktonic foraminifer composition shows that, despite their low diversity in general, changes in foraminiferal assemblages up the section reflect climatic fluctuations recognized worldwide by isotopic and paleontological studies. At the same time, dissolution and, probably, some other processes affecting the primary foraminiferal composition substantially distort the respective trends in some cases.

A significant modification of the initial foraminifer composition can probably be exemplified by their extremely impoverished late Paleocene assemblage of five species represented by single specimens. In view of the fact that sea surface temperatures were high at that time (e.g., Shackleton and Kennett, 1975; and others), such a low diversity and abundance of foraminifers could be related to both the dissolution of fossils and significant dilution of sediments by volcanic ash, which is the dominant rock component in the Paleocene interval. It is not inconceivable that falling volcanic material onto the sea surface created unfavorable conditions for the habitat and reproduction of planktonic foraminifers.

The most diverse (17 species) and well preserved assemblage of early Eocene foraminifers reflects warm-water environments. This is also confirmed by the prevalence of *Acarinina* and the abundance of keeled *Morozovella* species (*Morozovella subbotinae, M. aragonensis, M. formosa gracilis, M. lensiformis,* and *M. caucasica*). Representatives of these two genera, which, according to the classification of Boersma and Premoli Silva (Boersma *et al.,* 1987; Boersma and Premoli Silva, 1991), are considered to be the most thermophilic, migrated into higher latitudes during the early Eocene maximum of warming, as is recorded in both the northern and southern hemispheres, e.g., in the Koryak–Kamchatka region (Krasheninnikov *et al.,* 1988), Australia-New Zealand region (Jenkins and Srinivasan, 1985; Krasheninnikov and Basov, 1986; Krasheninnikov *et al.,* 1988), Kerguelen Plateau (Huber, 1991; Berggren, 1992), and Falkland Plateau (Tjalsma, 1977). It is noteworthy that none of the keeled morozovellids or any other thermophilic species were observed in the lower Eocene sediments from the Maud Rise of the Antarctic region (Stott and Kennett, 1990).

The diversity of planktonic foraminifers in the middle Eocene remained as high as in the early Eocene; however, their composition suggests a more cold-water character of the assemblage. This is emphasized by the dominant role of the cold-water cosmopolitan species of the *Globigerina, Globorotaloides,* and *Catapsydrax* genera in the assemblage. Acarininids occur only at separate levels of this interval. Also present are single specimens of tropical–subtropical *Truncorotaloides rohri* and *Globigerinatheca index*, whereas representatives of other thermophilic genera, such as *Morozovella, Hantkenina,* and *Orbulinoides,* are completely missing in the middle Eocene sediments. The late Eocene(?)–early Oligocene assemblage of planktonic foraminifers includes seven species in total; they all belong to cosmopolitan *Globigerina, Globorotaloides,* and *Tenuitella* genera. Such a change in foraminifer composition and reduction in their diversity is in accordance with the respective trend of climatic cooling recorded worldwide by oxygen isotope data.

A similar trend of changes in planktonic foraminifer composition and diversity has been recorded in Paleogene sections of the Koryak–Kamchatka region (Krasheninnikov *et al.,* 1988). Here, the most diverse assemblages are characteristic of the lower Eocene deposits, where they are dominated by subbotinids and acarininids with an insignificant admixture of keeled morozovellids. Such a composition allowed the *Morozovella subbotinae* s.l. and *Morozovella aragonensis* s.l. zones of the Crimea–Caucasus scale to be recognized in the lower Eocene interval. The middle Eocene assemblage, comparable in diversity with the early Eocene assemblage, lacks any thermophilic species. Only rare cosmopolitan planktonic foraminifers of no stratigraphic significance are present in the upper Eocene and Oligocene.

CONCLUSION

Drilling on the Obruchev Rise in the North Pacific during Leg 145 of the Ocean Drilling Program recovered the first Paleogene sections with calcareous planktonic microfossils, planktonic foraminifers included. The Paleogene assemblages of planktonic foraminifers in the studied area are relatively diverse (approximately 40 species) and, in many cases, well preserved. At the same time, when the relatively shallow-water environments of sedimentation are considered, their diversity here is lower than could be expected for the subtropical realm (south of 40°N) where, according to paleomagnetic data, the Obruchev Rise was situated during the Paleogene. The terminal Paleocene and the beginning of the Eocene were periods of the highest evolutionary activity of planktonic foraminifers (Corfield, 1987), which was also characteristic of the tropical–subtropical Pacific (Basov, 1993). The impoverished composition and low abundance of the late Paleocene foraminifers in the Obruchev Rise could, thus, be related either to unknown unfavorable living environments or to their burial conditions, and first of all, to the influence of selective dissolution. In composition and morphological peculiarities, planktonic foraminifers from the studied sections are similar to their coeval assemblages from various high-latitude areas of the northern and southern hemispheres, e.g., from New Zealand, the Campbell, Kerguelen, and Falkland plateaus, and from the Crimea–Caucasus and Koryak–Kamchatka regions.

The analysis of taxonomic composition of planktonic foraminifers and its changes through the section allowed the host sediments to be dated and subdivided. The presence of Paleocene, Eocene, and Oligocene sediments was established. In most cases, only major

stratigraphic units of the subseries rank are recognizable; zonal units are established only in the lower Eocene interval. The absence or discrete occurrence of many zonal species of the standard tropical foraminiferal scale hinders its application here. The most suitable for subdivision of this interval is the less detailed scheme of the Crimea–Caucasus zonal biostratigraphy.

Changes in planktonic foraminifer composition reflect global climatic fluctuations of the Paleogene time established by a number of paleontological data and oxygen isotope studies. The most diverse foraminifer assemblage represented mainly by thermophilic species is characteristic of the early Eocene. The middle Eocene–Oligocene interval is marked by a progressively decreasing diversity of foraminifers with the replacement of their thermophilic species by cosmopolitan forms.

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Reviewer M.A. Akhmet'ev

REFERENCES

Barron, J.A., Basov, I.A., Beaufort, L., *et al.*, Biostratigraphic and Magnetostratigraphic Summary, *Proceedings of the ODP, Scientific Results,* Rea, D.K., Basov, I.A., Scholl, D.W., and Allan, J.F., Eds., College Station: ODP, 1995, vol. 145, pp. 559–575.

Basov, I.A., Evolution of Planktonic Foraminifers of the Warm-Water Pacific in the Paleogene, *Stratigr. Geol. Korrelyatsiya,* 1993, vol. 1, no. 5, pp. 72–80.

Basov, I.A., Paleogene Planktonic Foraminifer Biostratigraphy of Sites 883 and 884, Detroit Seamount (Subarctic Pacific), *Proceedings of the ODP, Scientific Results,* Rea, D.K., Basov, I.A., Scholl, D.W., and Allan, J.F., Eds., College Station: ODP, 1995, vol. 145, pp. 157–170.

Beaufort, L. and Olafsson, G., Data Report: Upper Cretaceous and Paleogene Calcareous Nannofossils from the North Pacific, *Proceedings of the ODP, Scientific Results,* Rea, D.K., Basov, I.A., Scholl, D.W., and Allan, J.F., Eds., College Station: ODP, 1995, vol. 145, pp. 633–638.

Berggren, W.A., Paleogene Planktonic Foraminifer Magnetobiostratigraphy of the Southern Kerguelen Plateau (Sites 747–749), *Proceedings of the ODP, Scientific Results,* Wise S.W. and Schlich, R., Eds., College Station: ODP, 1992, vol. 120, pt. 2, pp. 551–568.

Berggren, W.A., Kent, D.V., and Flynn, J.J., Jurassic to Paleogene: Part 2. Paleogene Geochronology and Chronostratigraphy, *Mem. Geol. Soc. London,* 1985, vol. 1, pp. 141–195.

Blow, W.H., Late Middle Eocene to Recent Planktonic Foraminiferal Bostratigraphy, *Proc. First Intern. Conf. Planktonic Microfossils,* Bronnimann, P. and Renz, H.H., Eds., Geneva: Brill, 1969, vol. 1, pp. 199–422.

Boersma, A. and Premoli Silva, I., Distribution of Paleogene Planktonic Foraminifera–Analogies with the Recent?, *Palaeogeogr., Palaeoecol., Palaeoclimatol,* 1991, vol. 83, pp. 29–48.

Boersma, A., Premoli Silva, I., and Shackleton, N.J., Atlantic Eocene Foraminiferal Paleohydrological Indicators and Stable Isotope Paleoceanography, *Paleoceanography,* 1987, vol. 2, no. 3, pp. 287–331.

Bolli, H.M., Planktonic Foraminifera from the Eocene Navet and San Fernando Formations of Trinidad, B.W.I., *Bull. US Nat. Mus.,* 1957a, vol. 215, pp. 155–172.

Bolli, H.M., Planktonic Foraminifera from the Oligocene-Miocene Cipero and Lengua Formations of Trinidad, B.W.I., *Bull. US Nat. Mus.,* 1957b, vol. 215, pp. 97–123.

Bolli, H.M., The Genera *Globigerina* and *Globorotalia* in the Paleocene–Lower Eocene Lizard Springs Formation of Trinidad, B.W.I., *Bull. US Nat. Mus.,* 1957c, vol. 215, pp. 61–68.

Bolli, H.M., Zonation of Cretaceous to Pliocene Marine Sediments Based on Planktonic Foraminifera, *Bol. Inform. Asoc. Venez. Geol. Miner. Petrol,* 1966, vol. 9, no. 1, pp. 3–32.

Bolli, H.M. and Premoli Silva, I. Oligocene to Recent Planktonic Foraminifera and Stratigraphy of the Leg 15 Sites in the Caribbean Sea, *Initial Rep. Deep Sea Drill. Project,* Washington: US Gov. Print. Off., 1973, vol. 15, pp. 475–497.

Corfield, R.M., Patterns of Evolution in Palaeocene and Eocene Planktonic Foraminifera, *Micropalaeontology of Carbonate Environments,* Hart, M.B., Ed., London: Ellis Harwood, 1987, pp. 93–100.

Creager, J.S., Scholl, D.W., *et al., Initial Reports of the Deep Sea Drilling Project,* Washington: US Gov. Print. Off., 1973, vol. 19.

Huber, B.T., Paleogene and Early Neogene Planktonic Foraminifer Biostratigraphy of Sites 738 and 744, Kerguelen Plateau (Southern Indian Ocean), *Proc. of the ODP, Scientific Results,* Barron J. and Larsen B., Eds., College Station: ODP, 1991, vol. 119, pp. 427–449.

Jenkins, G.D., New Zealand Cenozoic Planktonic Foraminifera, *Bull. Paleontol. N.Z. Dept. Sci. Industr. Res., N.Z. Geol. Surv.,* 1971, vol. 42. pp. 1–178.

Jenkins, D.G. and Srinivasan, M.S., Cenozoic Planktonic Foraminifers from the Equator to the Subantarctic of the Southwest Pacific, *Initial Rep. Deep Sea Drill. Project,* Washington: US Gov. Print. Off., 1986, vol. 90, pp. 795–834.

Krasheninnikov, V.A., The Cenozoic Zonal Scale for Continents and Oceans, in *Stratigrafiya v issledovaniyakh Geologicheskogo instituta AN SSSR* (Stratigraphy in Research Projects of the Geological Institute, Academy of Sciences of the USSR), Moscow: Nauka, 1980, pp. 162–207.

Krasheninnikov, V.A., *Stratigrafiya paleogena severo-zapadnoi chasti Tikhogo okeana* (Paleogene Stratigraphy of the Northwestern Pacific), Moscow: Nauka, 1982.

Krasheninnikov, V.A. and Basov, I.A., *Stratigrafiya kainozoya Yuzhnogo okeana* (Cenozoic Stratigraphy of the Southern Ocean), Moscow: Nauka, 1986.

Krasheninnikov, V.A. and Basov, I.A., Late Mesozoic and Cenozoic Stratigraphy and Geological History of the South Atlantic High Latitudes, *Palaeogeogr., Palaeoclimatol., Palaeoecol,* 1986, vol. 55, pp. 145–188.

Krasheninnikov, V.A. and Hoskins, R.H., Late Cretaceous, Paleogene and Neogene Planktonic Foraminifera, *Initial Rep. Deep Sea Drill. Project,* Washington: US Gov. Print. Off., 1973, vol. 20, pp. 105–203.

Krasheninnikov, V.A., Serova, M.Ya., and Basov, I.A., *Stratigrafiya i planktonnye foraminifery paleogena vysokikh shirot Tikhogo okeana* (Paleogene Stratigraphy and Planktonic Foraminifers from High Latitudes of the Pacific Ocean), Moscow: Nauka, 1988.

Krasheninnikov, V.A., Serova, M.Ya., and Basov, I.A., Paleogene Zonal Scales Based on Planktonic Foraminifers and Their Significance in Elaboration of Paleogene Stratigraphic Scheme for the Pacific High Latitudes, in *Centenary of Japanese Mecropaleontology*, Tokyo: Terra Scientific, 1992, pp. 129–141.

Olafsson, G. and Beaufort, L. ,Data Report: Oligocene–Pleistocene Calacareous Nannofossils from Leg 145, *Proceedings of the ODP. Scientific Results,* Rea, D.K., Basov, I.A., Scholl, D.W., and Allan, J.F., Eds., Colleg, 1995, vol. 145, pp. 577–596.

Premoli Silva I. and Bolli, H.M., Late Cretaceous to Eocene Foraminifera and Stratigraphy of the Leg 15 Sites in the Caribbean Sea, *Initial Reports of the DSDP,* Washington: US Gov. Print. Off., 1973, vol. 15, pp. 449–547.

Rea, D.K., Basov, I.A., Janecek, T.R., *et al., Proc. of the Ocean Drilling Project, Initial Reports,* College Station: ODP, 1993, vol. 145.

Rea, D.K., Basov, I.A., Scholl, D.W., *et al., Proceedings of the Ocean Drilling Project, Scientific Results,* College Station: ODP, 1995a, vol. 145.

Rea, D.K., Basov, I.A., Krissek, L.A., and the Leg 145 Scientific Party, Scientific Results of Drilling the North Pacific Transect, *Proc. of the ODP. Scientific Results,* Rea, D.K., Basov, I.A., Scholl, D.W., and Allan, J.F., Eds., *College Station: ODP,* 1995b, vol. 145, pp. 577–596.

Shackleton, N. J. and Kennett, J.P., Paleotemperature History of the Cenozoic and the Initiation of Antarctic Glaciation: Oxygen and Carbon Isotope Analyses in DSDP Sites 277, 279 and 281, *Initial Rep. Deep Sea Drill. Project,* Washington: US Gov. Print. Off., 1975, vol. 29, pp. 743–756.

Shutskaya, E.K., Early Paleogene Stratigraphy, Foraminifers, and Paleogeography of the Crimea, Cis-Caucasus, and Western Part of Central Asia, *Tr. VNIGRI,* 1970, no. 7.

Stott, I.D. and Kennett, J.P., Antarctic Paleogene Planktonic Foraminifer Biostratigraphy: ODP Leg 113, Sites 689 and 690, *Proceedings of the ODP, Scientific Results,* Barker, P.F. and Kennett, J.P., Eds., College Station: ODP, 1990, vol. 113, pp. 549–569.

Subbotina, N.N., Globigerinids, Hantkeninids, and Globorotaliids, *Tr. VNIGRI,* 1953, no. 76.

Tjalsma, R.C., Cenozoic Foraminifera from the South Atlantic, DSDP Leg 36 , *Initial Rep. Deep Sea Drill. Project,* Washington: US Gov. Print. Off., 1977, vol. 36, pp. 493–517.

Toumarkine, M. and Luterbacher, H., Paleocene and Eocene Planktic Foraminifera, in *Plankton Stratigraphy,* Bolli, H.M., Saunders, J.B., and Perch-Nielsen, K., Eds., Cambridge: Cambridge Univ., 1985, pp. 87–154.

Stratigraphy and Geological Correlation, Vol. 5, No. 6, 1997, pp. 572–583. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 5, No. 6, 1997, pp. 51–63.
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Palynostratigraphic Subdivision and Correlation of Paleogene–Miocene Deposits in the Amgun–Gorin Region (Middle Courses of the Amur River)

L. A. Baskakova

All-Russia Institute of Geology, Srednii pr. 74, St. Petersburg, 199026 Russia

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Abstract—Palynological data are used for the first time to subdivide in detail the Paleogene–Miocene deposits filling intracontinental depressions in the Amgun–Gorin region. Twelve pollen assemblages are distinguished in the composite section (middle Eocene–upper Miocene) studied and divided into respective biostratigraphic units of local significance indicated as palynofloral beds. Lithological and palynological data obtained show that the main part of the section comprising the interval from the mid-middle Eocene to the lower Miocene correlates well with coeval deposits in adjacent areas and thus suggests that the whole Far East region was controlled by a common trend of the Cenozoic geological evolution. Two stratigraphic intervals above the coal-bearing beds (in the middle and terminal upper Miocene) are lacking pollen remains, and this presumably points to local breaks in sedimentation.

Key words: *Amur River, middle courses, Eocene, Miocene, continental deposits, subdivision, correlation, palynostratigraphy, vegetation, climate.*

The Paleogene and Miocene of the Amgun-Gorin area, as everywhere in the continental part of the Far East, comprise only terrestrial sedimentary and volcanic rocks, the latter being disregarded in this work.

The Cenozoic accumulative structures of the region represent the intracontinental depressions of the graben and, occasionally, of the basin types. Two linear groups of the depressions, the Amgun and Kur–Gorin zones, are separated by the Bodzhal Uplift (Fig. 1).

The Amgun zone extends northeastward along the Amgun River from its upper to middle courses. It includes the southern Ayakit–Suluk basin, Verkhnii Amgun graben, two small unnamed grabens at the left-hand side of the Amgun River, and the Omogun depression.

The Kur–Gorin zone covers the Gorin River basin and the upper courses of the Kur River. This arc-shaped zone comprises depressions arranged in an echelon manner and changing their strikes from latitudinal in the south to submeridional in the north. In passing from the southwest to the northeast, these are the Verkhnii Kur, Elga–Gorin, Gaichan, Khogdu–Gorin, Lian, Khurmulin, and Kharpin depressions.

As compared to other regions of the Far East (Primor'e, middle courses of the Amur River, and Amur–Zeya plain), Cenozoic deposits of the Amgun–Gorin area are poorly studied in stratigraphic aspect, and respective special investigations have never been carried out here. For a long period, data on sediments filling the Cenozoic depressions were fragmentary and based on general results of the geological survey obtained by M.L. Savitskii, A.F. Atamanchuk, N.K. Osipova, N.G. Osipov, A.F. Maiboroda, O.F. Kolodeznyi, A.I. Bukhanchenko, and E.A. Tin'kov.

Beginning from the mid-1970s, the necessity of prospecting and exploration of coal deposits activated the medium- and large-scale geological and hydrogeological study on the pre-Quaternary part of the Cenozoic that was performed under the guidance of B.S. Arkhipov and V.N. Pershin.

This study involved intense core drilling and palynological sampling and provided a reliable basis for the detailed subdivision of the Cenozoic. However, at present, the subdivision can be reliably substantiated only by palynoflora, because data on other organic remains (megaflora, diatoms) are scarce and usable only as supplementary arguments in solving some local problems.

As far as it concerns the palynology of Paleogene–Miocene deposits of the Amgun–Gorin region, I should mention here that in various periods it was studied by M.V. Ziva, J.I. Bityutskaya, L.I. Lukashova, I.B. Mamontova, G.S. Mal'tseva, N.D. Litvinenko, V.P. Sharova, O.N. Zhezhel', and A.V. Potapova, who contributed much to the issue. However, the available data have never been systematically analyzed and published, excluding a brief synopsis on the Cenozoic of the Gorin group of depressions that was included into the regional stratigraphic scheme of Paleogene–Neogene deposits of the Far East (Baskakova and Gromova, 1982).

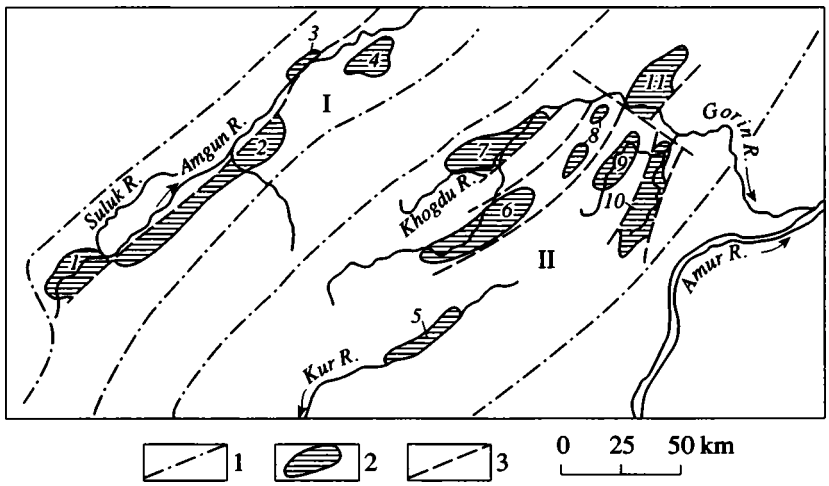

Fig. 1. Geographic scheme of Cenozoic accumulative structures of the Amgun–Gorin region: (1) boundary between zones; (2) depression; (3) fault; (I) Amgun zone; (II) Kur–Gorin zone.

(*1–11*) depression names: (*1*) Ayakit–Suluk; (2) Verkhnii Amgun; (*3*) Levyi Amgun; (*4*) Omogun; (*5*) Verkhnii Kur; (*6*) Elga–Gorin; (*7*) Khogdu–Gorin; (*8*) Gaichan; (*9*) Khurmulin; (*10*) Lian; (*11*) Kharlin.

In this work, I present the analytical synthesis of data obtained by the aforementioned researchers and the palynostratigraphic correlation of many studied sections (Fig. 2) that is used as a basis for the elaborated local stratigraphic scale (see table).

According to their lithologic features, Paleogene–Miocene deposits are divisible into two parts different in thickness and formation time. The greater Eocene–Miocene part consists of coal-bearing deposits overlain by the thinner Miocene sediments.

The most complete palynological characteristics are available only for the coaliferous interval, which yielded eleven successive pollen assemblages (PA).

The succession of the third to the eleventh assemblages inclusive (PA_3–PA_1) is detected on the basis of sections of the Khurmulin, Lian, and Verkhnii Amgun depressions, where data were collected applying the bed-by-bed method. Two lower pollen assemblages (PA_1 and PA_2) were distinguished in the Omogun depression only. The less detailed palynological data for other depressions allowed me to outline their pollen assemblages in a more general, sometimes tentative, manner (Fig. 3).

The composite section of sediments of the Amgun–Gorin region includes two coal-bearing intervals (Eocene and Oligocene–middle Miocene) separated by barren clayey deposits comprising the upper Eocene and basal lower Oligocene (Fig. 2).

The three-member structure of coaliferous deposits in question is accepted in the last stratigraphic scheme of Paleogene–Neogene deposits of Primor'e and the Amur River region suggested at the IV Interdepartmental Stratigraphic Conference (Khabarovsk, 1990) and validated by the Interdepartmental Stratigraphic Committee in 1991.

The lower coaliferous sequence is recovered in the Omogun depression alone, although its presence in deep-seated parts of other depressions untouched by drilling cannot be excluded. Outside the region under consideration, the Eocene coal-bearing sediments are known in the Evoron–Chukchagir basin (Lukashova and Mal'tseva, 1987).

In the Omogun depression, the coaliferous beds underlying the 12-m-thick member of Neogene (?) clays were penetrated by drilling only down to the depth of 125 m, although the basement in the central part of this structure lies at the depth of 500 m, according to the geophysical data. According to E.A. Tin'kov, deposits here display a high facial variability, and, in the marginal zones, they are represented by coarse-grained sediments of the piedmont aprons and alluvial cones replacing the coal-bearing lacustrine to palustrine facies.

In the lower coal-bearing beds, Lukashova and Mal'tseva distinguished two pollen assemblages (PA_1 and PA_2) with similar dominant and subdominant species but different compositions of accessory components, which are most diverse in PA_1 (Fig. 3). The background pollen composition of both assemblages is represented by Taxodiaceae, *Pinus* spp., *Picea* sp., *Tsuga* sp., *Alnus* sp., *Beluta* sp., *Quercus* sp., and *Ulmas* sp. A considerably lower pollen content (usually less than 2–3%) is characteristic of *Myrica* sp., *Carya* sp., *Juglans* sp., *Fagus* sp., *Carpinus* sp., *Liquidambar* sp., Rosaceae, and Ericaceae.

Both assemblages also include diverse accessory components, such as *Pterocarya* sp., *Platycarya* sp., *Engelhardtia* sp., *Quercus gracilis* Boitz., *Quercus sparsa* Mart., Moraceae, *Magnolia* sp., *Loranthus* sp., *Elytranthe* sp., *Corylopsis* sp., *Altingia* sp., Hamamelidaceae, *Ilex* sp., *Rhus* sp., *Ulmoideipites tricostatus*

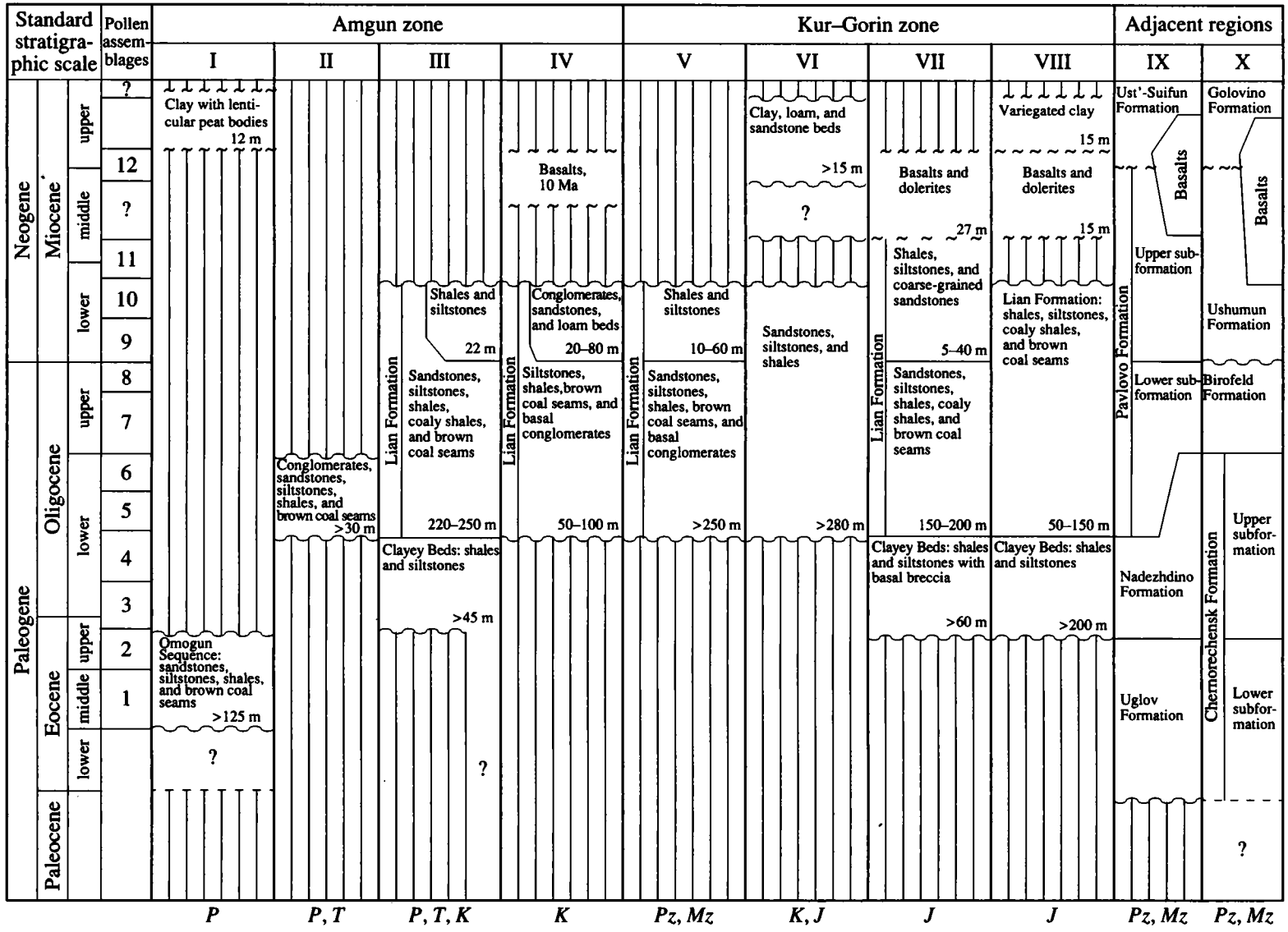

Fig. 2. Correlation scheme of the Paleogene–Miocene deposits in the Amgun–Gorin region. (I–VIII) sections of particular depressions: (I) Omogun (after data of E.A. Tin'kov, G.S. Mal'tseva, and L.I. Lukashova); (II) Levyi Amgun (after data of O.F. Kolodeznyi and V.P. Sharova); (III) Verkhnii Amgun (after data of V.N. Pershin, M.V. Ziva, and N.D. Litvinenko); (IV) Ayakit–Suluk (after data of V.N. Pershin, A.I. Bukhanchenko, N.D. Litvinenko, and V.P. Sharova); (V) Elga–Gorin (after data of M.L. Savitskii, O.F. Kolodeznyi, A.F. Maiboroda, P.I. Bityutskaya, and L.L. Kazachikhina); (VI) Khogdu–Gorin (after data of O.F. Kolodeznyi, B.S. Arkhipov, and I.B. Mamontova); (VII) Lian (after original data and materials of V.N. Pershin, P.I. Bityutskaya, and O.N. Zhezhel'); (VIII) Khurmulin (after data of V.N. Pershin, B.S. Arkhipov, N.D. Litvinenko, and V.P. Sharova); (IX) western Primor'e; (X) middle courses of the Amur River.

Local palynostratigraphic units of the Paleogene and Miocene in the Amgun–Gorin region

Standard stratigraphic scale			Local stratigraphic units	Pollen assemblages	Floral beds	Vegetation
Neogene	Miocene	upper	Clays	PS	*Tsuga diversifolia–Picea*–Betulaceae	Dark coniferous–small-leaved forest
				PS	*Tsuga diversifolia–Picea*–Taxodiaceae	Dark coniferous forest
				PA_{12}	*Tsuga diversifolia*–Taxodiaceae–Juglandaceae	Mixed forest vegetation of temperate climatic zone
		middle	Basalts	?		
		lower		PA_{11}	*Pinus excelsoeformis–Tsuga crispa–Pterocarya*	Coniferous forest with accessory foliaceous plants
				PA_{10}	Taxodiaceae–*Juglans sibirica–Carpinus betalus*	Mixed forest vegetation of temperate climatic zone
				PA_9	*Tsuga crispa–Picea obovata–Quercus mongolica*	Coniferous–foliaceous vegetation with accessory broad-leaved taxa
Paleogene	Oligocene	upper (Chattian)	Upper coaliferous sequence (Lian Formation)	PA_8	Pinaceae–Betulaceae–Rosaceae	Small-leaved–fruticose and small-leaved coniferous vegetation
				PA_7	*Tsuga crispa–Picea alata–Pterocarya oligocenica*	Coniferous–small-leaved vegetation with accessory broad-leaved plants
		lower (Rupelian)		PA_6	Pinaceae–*Quercus conferta–Quercus mongolica*	Coniferous–broad-leaved forest of temperate climatic zone
				PA_5	*Pinus strobiformis–Tsuga crispa–Carya spacmania*	Diverse coniferous forest with accessory small- and broad-leaved taxa
				PA_4	Pinaceae–Betulaceae–*Ulmoideipites tricostatus*	
			Nonproductive (clayey) beds	PA_3	Taxodiaceae–*Myrica–Ulmoideipites tricostatus*	Coniferous–broad-leaved forest of temperate climatic zone
	Eocene	upper	Lower coaliferous (Omogun) sequence	PA_2	Taxodiaceae–*Quercus graciliformis–Tricoipopollenites liblarensis*	Mesophilic vegetation with accessory subtropical plants
		middle		PA_1	*Quercus graciliformis–Castanea crenataeformis–Tricolporopollenites cingulum*	Subtropical vegetation
			?	PS – pollen spectrum		
		lower				

And., *Platanus* sp., *Tilia* sp., *Nyssa* sp., *Aralia* sp., *Sterculia* sp., *Triatriopollennites plicoides* Zakl., and *Tricolpopollenites liblarensis* Th.

In addition, the lower assemblage PA_1 includes rare, often solitary, grains of Palmae, *Comptonia* sp., *Castanea crenataeformis* Samig., *C. crenata* Sieb. et Zucc, *Castanopsis pseudocingulum* (R. Pot.) Boitz., *Quercus graciliformis* Boitz., *Q. conferta* Boitz., *Ulmoideinites krempii* And., *Corylopsis compacta* Lubm., *Proteacedites formosus* Sam., *Loranthus elegans* I. Kulk., *Rhus coriariformis* Boitz., *Pokrovskaja granularis* Boitz., *Triporopollenites plectosus* Pfl., and *Tricolporopollenites cingulam* (R. Pot.) Th. et Pfl. These taxa coexist with sporadic Cretaceous–Paleocene pollen of *Tricolpites erdtmani* Zakl., *T.* aff. *matauraensis* Couper., *Gothanipollis* sp., *Mancicorpus* sp., *Barapollis* sp., *Complexipollis* sp., and with spores of *Matenia* sp. and *Concavisporitus* sp.

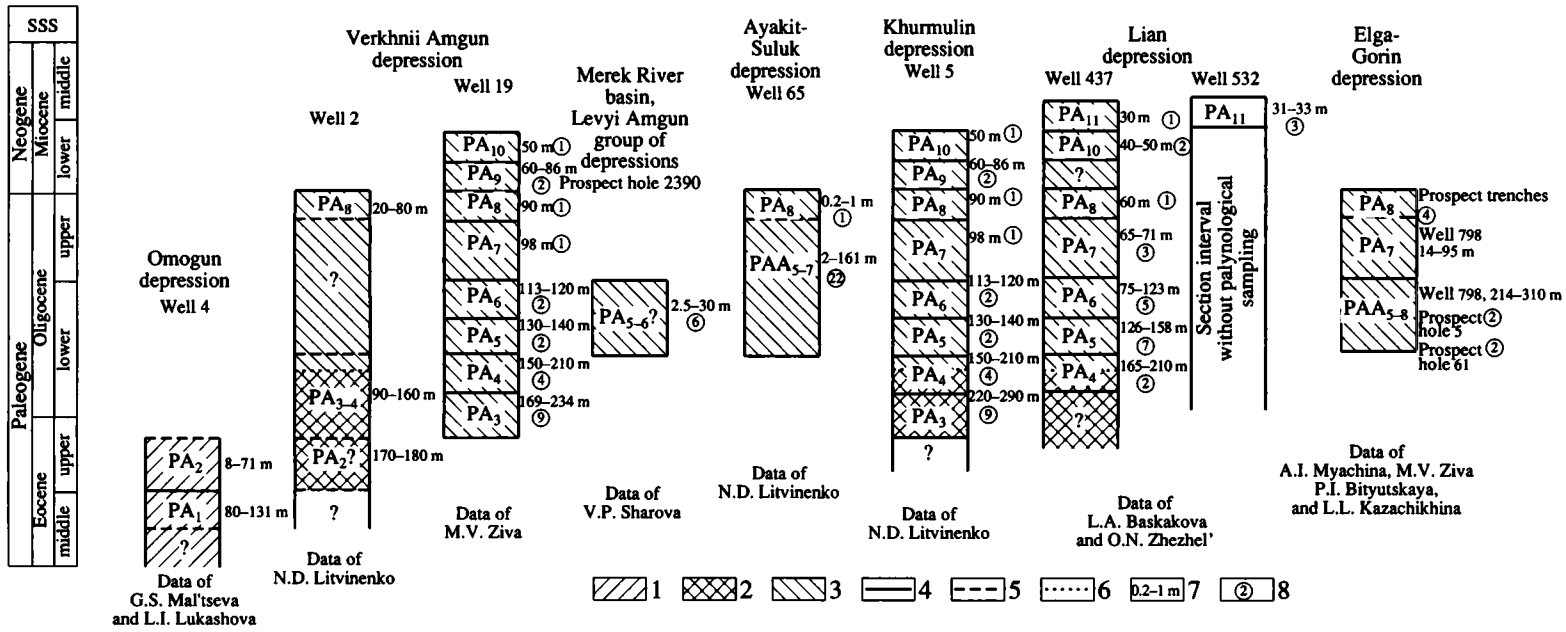

Fig. 3. Distribution of pollen assemblages in coaliferous sequences of Cenozoic depressions in the Amgun–Gorin region: (1) lower coaliferous sequence; (2) nonproductive Clayey Beds; (3) upper coaliferous sequence; (4) boundary between pollen assemblages; (5) hypothetical boundary between pollen assemblages; (6) boundary between sequences; (7) depth of palynological sampling; (8) number of samples; (SSS) Standard stratigraphic scale.

Lukashova and Mal'tseva referred the lower assemblage to the upper Eocene and considered the second one as corresponding to the lower Oligocene.

In my opinion, they both are of the Eocene age. The lower assemblage with taxonomically diverse Fagaceae and other representatives of the thermophilic Eocene palynoflora is correlative with the chronological level of the Eocene climatic optimum. A higher content of Pinaceae pollen in the second assemblage still containing characteristic Eocene taxa suggest that it is of a more temperate type and represents vegetation formed at the decline of the late Eocene warming stage.

With certain doubts, PA_2 can be correlated with a pollen assemblage detected by Litvinenko in basal beds of the 40-m-thick member of clay that was recovered by Well 2 under weakly coaliferous sands and clays (the upper coal-bearing interval) in the northwestern part of the Verkhnii Amgun depressions. The taxonomically diverse pollen of temperate broad-leaved and subtropical plants represents the main feature of the last assemblage.

Both PA_1 and PA_2 correlate well with pollen assemblages from the upper part of the Uglov Formation of the southern Primor'e (Baskakova and Gromova, 1982). Therefore, I assume that the lowermost beds of the Omogun section below the interval recovered by drilling may correspond to the lower part of this formation. In this connection, it seems reasonable to term the lower coaliferous beds as the "Omogun Sequence."

The coal-free clayey deposits were recovered by drilling under the upper coaliferous interval in the Verkhnii Amgun, Khurmulin, and Lian depressions. These deposits consist of monotonous gray, predominantly massive shales and siltstones intercalated with rare interlayers of fine-grained sandstones. In some sections, these sediments overlie lenticular basal beds of conglobreccia. The total thickness of this lithologic unit is up to 200 m.

The most complete palynological data on this clayey sequence were obtained by Litvinenko from the section of the Khurmulin depression. They provide the possibility to detect the bed-by-bed changes in palynoflora accordingly divisible into pollen assemblages PA_3 and PA_4.[1]

Basal beds of the upper coal-bearing interval recovered by Well 19 in the Verkhnii Amgun depression also yielded two pollen assemblages correlative with PA_3 and PA_4 (Fig. 3).

The third pollen assemblage from both structures is most rich in Taxodiaceae and *Alnus* specimens. *Myrica* sp. is among dominant taxa only in the Khurmulin section. Subdominant forms of PA_3 are *Picea* sp., *Pinus* sp., *Tsuga* sp., *Betula* sp., and three other taxa confined to its lower strata (*Corylus* sp., *Carpinus* sp., and *Ulmus* sp.). One more group of species rather abundant in PA_3 of the Verkhnii Amgun section is represented by pollen of *Quercus* sp. (0.5–1%), including *Q. graciliformis* Boitz. (0.5–1%) and *Q. conferta* Boitz. (1–2%).

As compared to the second assemblage, subtropical components of the third assemblage are less abundant and represented by infrequent pollen grains of *Comptonia* sp., *Liquidambar* sp., *Nyssa* sp., *Aralia* sp., and *Parthenocissus* sp. mainly concentrated in the lower strata. In addition, the last group of accessory taxa includes *Juglans* sp., *Carya* sp., *Pterocarya* sp., *Fagus* sp., *Castanea* sp., *Castanopsis* sp., *Ulmus* sp., Rosaceae, Ranunculaceae, and Leguminosae.

Some sporadic pollen grains in PA_3 belong to characteristic Eocene taxa identifiable in the artificial classification, namely, to *Ulmoideipites krempii* And., *U. planeraeformis* And., *U. tricostatus* And., *Elytranthe striatus* Couper., *Tricolpites* sp., and *Triatriopollenites* sp. I place the third assemblage at the Eocene–Oligocene boundary of the stratigraphic scale taking into account all its taxonomic peculiarities.

The fourth pollen assemblage (PA_4) is characteristic of the uppermost clayey beds and overlying basal strata of the upper coaliferous sequence. This assemblage demonstrates a considerably increased abundance of conifers. In the Khurmulin and Lian sections, this type of pollen is much more abundant than that of angiosperms; its content is as high as about 70% of all palynological remains. In the Verkhnii Amgun section, proportions of conifers and angiosperms are approximately equal.

The most abundant coniferous taxa of PA_4 are *Pinus* sp., *Picea* sp., *Tsuga* sp., and, to a lesser extent, Taxodiaceae. *Alnus* sp. (9–20%) and *Betula* sp. (5–10%) are dominant taxa among angiosperms. The content of *Quercus* pollen in PA_4 is still rather high in the Verkhnii Amgun section, and, in addition to *Quercus graciliformis* Boitz. (4%) and *Q. conferta* Boitz. (4%) inherited from older assemblages, this genus includes here the younger pollen of *Q. mongolica* Fisch. and *Q. sibirica* Pan., which was not registered in underlying beds.

Podocarpus sp., *Abies* sp., *Sparganium* sp., *Myrica* sp., *Juglans* sp., *Carya* sp., *Corylus* sp., *Carpinus* sp., *Fagus* sp., *Ulmus* sp., Moraceae, Ranunculaceae, Rosaceae, Leguminosae, *Altingia* sp., and *Ulmoideipites krempii* And. are present in PA_4 as rare or single grains. The assemblage is almost completely lacking taxa of the artificial classification.

In general, the fourth pollen assemblage corresponds to the coniferous locally mixed forest vegetation of the temperate climatic zone that included a notable amount of small-leaved Betulaceae and an admixture of broad-leaved plants. This type of "coniferous" pollen assemblages is known from basal beds of the lower Oligocene in Primor'e (Baskakova, 1990), Siberia (Panova, 1971; Laukhin and Kul'kova, 1978; Kul'kova and Volkova, 1994), the West Baikal region (Aleksandrova and Kozyar, 1978), and Crimea and the Caucasus

[1] Here I use the consecutive numbering of assemblages in the composite section.

(Panova *et al.*, 1990); it can be used in palynostratigraphic correlations as marking the respective reference level.

According to the conjoined time interval of PA_3 and PA_4, to which I also add the interval of PA_2 in the Verkhnii Amgun section, the age of clayey deposits can be identified as spanning the late Eocene and initial early Oligocene intervals. It should also be noted that this composite unit has diachronous boundaries (Fig. 3). Its lower limit marks the base of PA_3 and presumably that of PA_2; in other words, it lies at different levels of the upper Eocene. The upper boundary is in the interval of the upper Eocene–lower Oligocene beds.

On the basis of this age interpretation, lithologic composition, and position in the section (between two coal-bearing sequences), the clayey deposits under consideration can be correlated with the Nadezhdino Formation of the southern Primor'e. By the two last criteria, they also resemble the Birofeld Formation of the Srednii Amur depression, whose accepted age is, however, different. It would be useful to revise the available biostratigraphic data on this depression in order to solve the indicated discrepancy, because they have been interpreted this way since the 1960s.

The upper coal-bearing sequence is present in all sections excluding that of the Omogun depression. The sequence is composed of shales, siltstones, variably grained sandstones, coaly shales, and brown coal beds. In some sections, these rocks overlie basal conglobreccia beds. Sections of the Lian, Khurmulin, and Verkhnii Amgun depressions are the richest in coal beds of industrial significance.

The percentage of coal seams considerably decreases in the upper part of sections of the Verkhnii Amgun, Ayakit–Suluk, and Elga–Gorin depressions. The upper coaliferous sequence varies in thickness from 40 to 400 m.

The most representative sections of the upper coal-bearing deposits (the Lian, Khurmulin, and Verkhnii Amgun localities) yielded seven pollen assemblages (PA_{5-11}) with distinctly successive features reflecting phytoclimatic changes. They all display a stable predominance of conifers, mainly of Pinaceae. The abundance of dominant families and genera notably varies upsection, whereas the parallel taxonomic changes in accessory components are less evident.

In general, the fifth pollen assemblage (PA_5) is similar to PA_4; nonetheless, it has a less diverse taxonomic composition, thus reflecting further climatic cooling. Pollen of *Tsuga* (20%) and Pinaceae (20%) includes *Tsuga crispa* Zakl., *T. torulosa* Zakl., *T.* sp., *Pinus* sp., *P. excelsaeformis* Zakl., *P. strobiformis* Zakl., *P. protocembra* Zakl., and *P. cristata* Pan., and it is dominant in this assemblage. *Alnus* forms (18–20%) are most abundant among angiosperms. *Abies* sp. (5%), *Picea* sp. (up to 10%), and *Betula* sp. (4–6%) are subdominant taxa.

The content of Taxodiaceae pollen is usually below 3%, i.e., lower than in PA_4. The constantly present, though not abundant (1–2%), components of PA_5 are *Ginkgo* sp., *Podocarpus* sp., *Myrica* sp., *Juglans* sp., *J. sieboldianiformis* Vojc., *Corylus* sp., *Carpinus* sp., *Ilex* sp., *Rhus* sp., Gramineae, and Cyperaceae.

Carya spacmania Trav. and *Quercus conferta* Boitz., characteristic of the Oligocene along with Eocene species *Castanea crenataeformis* Samig., occur sporadically. Single grains of formal taxa representing relics of the Late Cretaceous–Early Paleogene flora, such as *Aqulapollentes* sp. and *Triporina globosa* Chlon., were encountered in one spectrum only. Polypodiaceae (4–8%) and *Osmunda* sp. (1–20%) are the principal components of the spore fraction. They associate with non abundant or scarce spores of *Sphagnum* sp., *S. putillum* Drozh., *S. stictum* Wolff., *Lycopodium* spp., *Selaginella* sp., and *Coniopteris* sp.

According to its position in the section, PA_5 can be referred to the middle part of the lower Oligocene. A similar pollen assemblage with abundant and diverse Pinaceae is known from the lower Oligocene of the Evoron–Chukchagir depression (Lukashova and Mal'tseva, 1987); however, it includes the more diverse pollen of meso- and thermophilic plants, as compared to PA_5. The last depression is located to the north from our localities, and this suggests that both comparable assemblages mark not one but two closely spaced levels of the lower Oligocene.

The sixth pollen assemblage (PA_6), which was distinguished in the very thin interval of the section, corresponds to a short period of climatic warming.

Pollen of Pinaceae of the same generic and specific composition, though somewhat less abundant than in PA_5, still retains its leading position at this level. The content of Taxodiaceae pollen increases here up to 10%. In the Verkhnii Amgun locality, the abundance of Taxodiaceae and Pinaceae pollen may sometimes be as high as 25%.

At the time in question, the content of small-leaved *Alnus* spp. (maximum 10%) and *Betula* sp. (up to 3%) decreased in the group of angiosperms, whereas their meso- and thermophilic forms, though also not abundant, became much more diverse in the taxonomic aspect.

Fagaceae, mainly various *Quercus* (6%) and *Castanea* forms, were dominant in the last group. They were represented by the ancient Eocene and Eocene–Oligocene species, such as *Q. graciliformis* Boitz., *Q. conferta* Boitz., *Castanea crenataeformis* Samig., and *Castanopsis pseudocingulum* (R. Pot.) Boitz., combined with the Oligocene–Miocene and present-day species *Q. forestdalensis* Trav., *Q. dentata* Thunb., and *Q. mongolica* Fisch.

Pollen of *Pterocarya* sp., *P. oligocenica* Vojc., *Caryites* sp., *C. ventricosus* Mart., *Juglans sieboldianiformis* Vojc., *J. polyporata* Vojc., *Platycarya* sp., *Corylus* sp., *Carpinus* sp., *C.* cf. *betulus* L., *C. orientalis* Mill., *Ulmus* sp., *Hamamelis* sp., *Liquidambar* sp., *Celtis* sp., *Rhus* sp., *R. coriariformis* Boitz., *Ilex* sp., and *Nyssa* sp. is low in abundance in PA_6 (1–2%).

Sporadic components of the assemblage are Palmae and Proteaceae. Its herbaceous forms PA_6 are *Sparganium* sp. (1%), Cyperaceae (9%), and *Lonicera* (1%). Sporiferous plants are represented by Polypodiaceae (4%), *Osmunda* spp. (18%), and rare *Sphagnum putillum* Drozh. and *Coniopteris* sp.

In comparison with similarly thermophilic PA_1, which is also enriched in Fagaceae, PA_6 shows a lower diversity of subtropical species and is simultaneously lacking the formal taxa and early Cenophytic relics. Furthermore, it includes the young *Quercus* species.

In general, PA_6 represents vegetation rich in dark conifers and incorporating an admixture of diverse mesophilic broad-leaved plants and thermophilic taxa. It is correlative with the short episode of climatic warming in the Pacific province at the end of the early Oligocene (Krasheninnikov *et al.*, 1989). This event is recorded in palynofloras of different regions. A similar transition from the basal "coniferous" pollen assemblages of the lower Oligocene to the coniferous–broad-leaved floras rich in representatives of Fagaceae and Juglandaceae was detected in sections of the Crimea, Caucasus, Aral region, western Siberia (Panova *et al.*, 1990), Primor'e (Gromova, 1984; Baskakova, 1990), and northeastern Russia (*Paleogen* ..., 1989).

In southern areas, where spore–pollen assemblages associate with other paleontological remains, such as planktonic foraminifers and nannofossils, the thermophilic Fagaceae–Juglandaceae floras are inferred to be the middle–late Rupelian in age. These floras differ from PA_6 of the Amgun–Gorin region by a higher content of angiosperms, whose taxonomic composition possibly reflects their origin in other geographic zones. Nevertheless, all the assemblages contain several correlative species, such as *Quercus gracilis* Boitz., *Q. conferta* Boitz., *Castanea crenataeformis* Samig., *Juglans polyporata* Vojc., and *J. sieboldianiformis* Vojc.

The seventh pollen assemblage (PA_7) corresponds, in contrast to PA_6, to the vegetation of a more temperate climate. It is of the coniferous–small-leaved type and rich in Pinaceae and Betulaceae, whereas the admixture of broad-leaved taxa is insignificant.

Dominant taxa of the assemblage are *Tsuga* spp. (12–25%), *Picea* sp. (10–15%), and *Alnus* sp. (15–30%). Its less abundant but constantly present components are represented by *Abies* sp. (4–5%), *Pinus* sp. (7–14%), Taxodiaceae (3–7%), and *Betula* sp. (3–13%). Occasional taxa, whose content is usually below 1%, are arboreal plants, such as *Myrica* sp., *Carya* sp., *Pterocarya* sp., *P. oligocenica* Vojc., *Juglans* sp., *J. sieboldianiformis* Vojc., *Corylus* sp., *Castanea* sp., *Quercus* sp., *Fagus* sp., *Ulmus* sp., *Rhus* sp., *Ilex* sp., and *Acer* sp., associated with herbaceous and fruticose species of *Sparganium* sp., Gramineae, Cyperaceae, Ericaceae, and *Diervilla* sp. Spores of the assemblage belong to Polypodiaceae (5–40%), *Osmunda* (1–25%), sometimes, to *Sphagnum* sp. (5%), and very rarely to *Lycopodium* sp., *Coniopteris* sp., *Gleichenia* sp., and *Leiotriletes* sp.

I refer PA_7 to the upper Oligocene and consider it as reflecting the commencement of cooling.

The eighth pollen assemblage (PA_8) is distinguished on the basis of few well-correlative pollen spectra characteristic of many depressions in the region (Fig. 3). In contrast to previous assemblages, this one corresponds to vegetation represented either by small-leaved fruticose and herbaceous plants or by small-leaved–coniferous forests.

In the Khurmulin depression, PA_8 (the depth level of 90 m) predominantly consists of Rosaceae representing 35% of the entire pollen mass. In addition to this group, it includes less abundant *Tsuga* sp. (3.3% for three species of the genus), *Picea* sp. (4.3%), *Pinus* sp. (7.6%), and *Alnus* sp. (9.5%). To complete the list of arboreal and fruticose taxa of the assemblage, it is necessary to mention also *Abies* sp., Taxodiaceae, *Myrica* sp., *Fagus* sp., *Corylus* sp., and *Quercus* sp. represented by rare pollen grains.

The taxonomic composition of herbaceous and sporiferous plants of PA_8 is impoverished. The most remarkable taxa of these groups are Cyperaceae (7%), Liliaceae (4%), Leguminosae (5%), and *Bryales* sp. (7%).

On the basis of its composition and stratigraphic level in the section, the assemblage can be correlated with pollen spectra detected by Litvinenko in the uppermost coaliferous beds of the Ayakit–Suluk (Well 65) and Verkhnii Amgun (Well 2) depressions. Principal plant groups in these spectra are also represented by small-leaved amentiferous trees (*Alnus, Betula*), fruticose forms, and forbs (Cyperaceae, Gramineae, Liliaceae, Rosaceae, Ericaceae, *Lonicera*, Onagraceae, *Artemisia*, Compositae, and others).

The taxonomic impoverishment and distinct transformation of vegetation recorded in this assemblage allow me to support conclusions of Litvinenko and to correlate this flora with a sharp climatic cooling in the terminal late Oligocene (Chattian), right before the Miocene. This event was very important for biota evolution in the Far East.

In the Lian depression, the same stratigraphic level (the depth of 60 m) yielded again the impoverished pollen assemblage of the dark-conifers–birch–alder type. Its dominant forms are the dark conifers, such as *Tsuga* sp. (25%), *Picea* sp. (13%), and *Abies* (5%), and small-leaved Betulaceae, namely *Alnus* (18%) and *Betula* (9%). Diverse Pinaceae (14%) are also rather abundant here and include *Pinus exelsaeformis* Zakl., *P. strobiformis* Zakl., and *P. cristata* Pan. Taxodiaceae (5%) and *Carpinus* (3%) are the taxa succeeding them in abundance, and *Carya* sp., *Pterocarya* sp., and *Juglans* sp. are represented by scanty pollen grains.

M.V. Ziva and A.I. Mechina identified similar pollen spectra with a high abundance of Pinaceae and small-leaved Betulaceae in the coal-bearing deposits of the

Elga–Gorin depression, where they were recovered by stripping trenches.

Changes in palynofloras at the upper levels of coaliferous deposits suggest a new stage of climatic warming. These floras display a higher content of Taxodiaceae pollen and more variable composition of meso- and thermophilic taxa. This stratigraphic interval includes the ninth (PA_9) and tenth (PA_{10}) pollen assemblages.

Pinaceae and Betulaceae are still the dominant groups of PA_9. Main components of the first group are represented by the diverse *Tsuga* species, such as *T. crispa* Zakl., *T. torulosa* Zakl., *T. canadensis* Carr., and *T. diversifolia* (Max.) Mast., whose content can be as high as 30%; pollen of *Picea* sp. (12–22%) and *Pinus* sp. (4–16%) is somewhat less abundant. A persistent admixture of *Abies* sp. and *Larix* sp. is also characteristic of the group.

Alnus sp. (8–35%) and less abundant *Betula* sp. (1–6%) and *Corylus* sp. (1%) are the principal components of the Betulaceae.

Subdominant taxa of the assemblage are Taxodiaceae (4–10%) and genera *Sparganium* (2.5–10%) and *Quercus* (3.5–6%), the latter represented only by young species, such as *Q. sibirica* Pan., *Q. mongolica* Fisch., and *Q. dentata* Thunb.

The accessory components of the assemblage are quite diverse and include arboreal, fruticose, and herbaceous species. Characteristic taxa of this fraction are represented by *Myrica* sp. (0.5–3.5%), *Fagus* sp. (0.5–1.5%), *Ulmus* sp. (0.5–2.0%), *Juglans* sp. (1%), Rosaceae (1%), Ericaceae (0.5–3.5%), Cyperaceae (0.5–1.5%), and Ranunculaceae (1%). Other minor components, whose content is usually below 1%, are *Carya* sp., *Liquidambar* sp., *Hamamelis, Rhus* sp., *Ilex* sp., *Acer* sp., Leguminosae, *Baisduvalia* sp., Onagraceae, *Sphagnum* sp., *Bryales* sp., *Lycopodium* sp., *Osmunda* sp., *Adiantum* sp., and *Botrychium* sp.

In general, PA_9 corresponds to small-leaved–coniferous forest vegetation with an admixture of diverse, though not abundant, meso- and thermophilic plants.

The tenth pollen assemblage (PA_{10}) differs from PA_9 in that it has a higher content of Taxodiaceae (17–20%), represented by *Taxodium* sp., *Sequoia* sp., *Glyptostrobus* sp., and *Sciadopites* sp. Species of Pinaceae are somewhat less abundant here, although they can still be classified as dominant and subdominant components with the following abundance ranges: *Tsuga* sp. (5–19%), *Picea* sp. (10–19%), and *Pinus* sp. (4–5%).

Angiosperms of PA_{10} display a higher significance of broad-leaved taxa, among which the most diverse and abundant are Juglandaceae (10–12%), represented by *Juglans sieboldianiformis* Vojc., *J. polyporata* Vojc., *J. sibirica* Vojc., *J.* sp., *Carya* sp., *Caryites* sp., *Pterocarya* sp., and *P. oligocenica* Vojc., and also the genus *Carpinus* (11%), exemplified by its species *C. betulas* L., *C. orientalis* Mill., and *C.* sp. The small-leaved Betulaceae, namely *Alnus* sp. (8–17%) and *Betula* sp. (4–7%), are also significant components of the assemblage, although, in contrast to PA_9, the oak group is represented here only by nonabundant pollen of *Quercus* sp. (up to 2.5%).

The group of accessory components of PA_{10} does not demonstrate changes at the family and generic levels.

I refer both PA_9 and PA_{10} to the early Miocene, as reflecting the climatic warming of that time. It should be noted, however, that they are not as meaningful as successive pollen assemblages of Primor'e, Kamchatka (Brattseva and Giterman, 1984), and northeastern Russia (Baranova *et al.*, 1979), where the peak Miocene warming is recorded by the presence of the Fagaceae pollen. In contrast, the abundance of the latter in the Miocene assemblages of the Amgun–Gorin region is insignificant, and this either indicates that these assemblages are incompatible with the maximum of that climatic optimum or points to the peculiar landscape and ecological features of the region.

I am apt to favor the last alternative, taking into account that pollen assemblages of the Fagaceae type are typical of plains, whereas, in the mountain areas of eastern Russia, the assemblages of the Miocene climatic optimum are not very rich in this group of taxa. In the latter areas, they display a high abundance of dark conifers, a considerable content of small-leaved Betulaceae, and a diverse admixture of broad-leaved plants (*Paleogen*, 1989). The same features are typical of our assemblages.

The eleventh pollen assemblage (PA_{11}) has a local distribution range. It was detected in a member of silty psammites at the top of coal-bearing deposits of the Lian depression. With due precautions, this assemblage can be correlated with the palynospectrum of silty pelites exposed below the Neogene basalts in the Sidorka River valley of the Ayakit–Suluk depression (Zhezhel' *et al.*, 1990). In other structures, the upper limit of coal-bearing deposits is at the level located between PA_8 and PA_{10}.

The impoverished palynoflora of PA_{11} reflects a considerable deterioration of the climate. Its angiosperms are less diverse and abundant than in PA_{10}. The dominant group here consists of Pinaceae (up to 32%), and especially abundant in composition are *Pinus silvestriformis* Zakl., *P. strobiformis* Zakl., *P. excelsaeformis* Zakl., and *P. taedaeformis* Zakl. Somewhat less abundant components are represented by the following *Tsuga* (up to 25%) and *Picea* (up to 17%) species: *T. crispa* Zakl., *T. torulosa* Zakl., *T.* sp., *P. oborvata* Ldb., *P. atata* Zakl., *P. gigantea* Boitz., and *P.* sp. coexisting with *Abies* sp. (4%). The content of Taxodiaceae (2–4%) is considerably lower than in PA_{10}.

Betulaceae and Juglandaceae, the main components of angiosperms, are less diverse and abundant. Their representatives are *Alnus* sp. (5–10%), *Betula* sp. (1–3%), *Carpinus* sp. (1–5%), *Pterocarya* sp. (3–5%), *P. oligocenica* Vojc. (up to 2%), *Juglans* sp. (1%), and

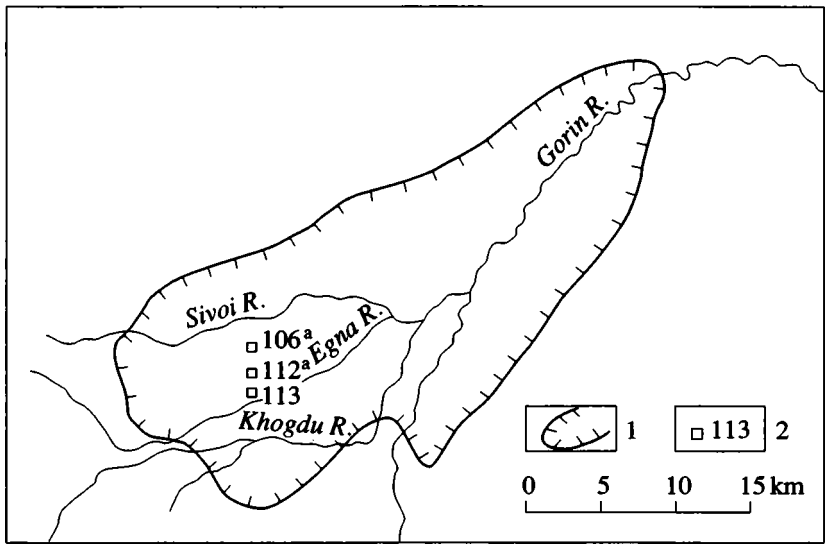

Fig. 4. Localities of sediments with the late Miocene pollen in the Khogdu–Gorin depression: (1) contour of depression; (2) prospect hole and its number.

rare pollen grains of *J. polyporata* Vojc. and *Platycarya* sp. Sporadic and single pollen specimens belong to *Myrica* sp., *M. glabraeformis* Stelm., *Fagus* sp., *Castanea* sp., *Ulmus* sp., *Zelkova* sp., *Rhus* sp., *Ilex* sp., *Acer* sp., *Tilia* sp., *Aralia* sp. and *Cornus* sp.

The content of herbaceous taxa, such as *Sparganium* sp., Gramineae, Liliaceae, Liguminosae, Violaceae, and *Artemisia*, is usually below 1%, and only Cyperaceae (3%) are more abundant. Polypodiaceae (8–10%), *Osmunda* sp. (2–8%), and *Sphagnum* sp. (1–2%) exemplify sporiferous plants of the assemblage. Judging from its composition, PA_{11} corresponds to coniferous forest vegetation with rather abundant Betulaceae and an insignificant admixture of mesophilic broad-leaved plants.

I assume the terminal early–initial middle Miocene age of the last assemblage.

According to the palynological data, the entire stratigraphic range of the upper coaliferous sequence comprises the Oligocene; locally it can be wider, extending from the topmost Eocene beds to the basal middle Miocene. Both boundaries of the sequence are diachronous: the lower one is inside the interval between the Eocene–Oligocene boundary strata and middle beds of the lower Oligocene, and the upper boundary lies between the top of the Oligocene and the basal middle Miocene. In my opinion, the age limits of the upper coal-bearing strata correspond to those of the highly productive Pavlovo Formation of coaliferous deposits in the southern Primor'e.

As noted above regarding the upper coaliferous sequence, the abundance of coal seams decreases upsection, thus providing grounds to divide these beds into two subformations. This feature is also compatible with the two-member structure of the Pavlovo Formation comprising the lower productive subformation and the upper tuffaceous unit with poor coal seams.

I believe that available stratigraphic and paleontological data on the widespread upper coaliferous sequence of the Amgun–Gorin region allow it to be classified in the rank of the formation. I suggest naming it the Lian Formation, as it is best represented and studied in the synonymous depression.

The Miocene deposits overlying the coal-bearing sequence are less widespread and insufficiently studied. They exemplify the terminal phase of the Eocene–Miocene megacycle of sedimentation. Areas of sediment accumulation considerably decreased at that time, and this finally resulted in the regional sedimentation break at the Miocene–Pliocene boundary before the commencement of new (Pliocene–Quaternary) megacycle of geological history of the Far East.

The "supracoal" Miocene sediments are reliably distinguished in the Khogdu–Gorin depression alone, where they are penetrated by prospect holes (1–5 m deep) at the right-hand side of the Sivoi River (Fig. 4) and were found to be bearing spore and pollen remains.

According to data of O.F. Kolodeznyi, these horizontally lying deposits consist of dense gray to gray-brown clays with lenticular interbeds of pebbles and coarse-grained sands; they are approximately 15 m thick. Beds underlying them have not been recovered, and only data of the aeromagnetic survey suggest that these deposits rest on the Miocene (?) basalts in the Sivoi–Khogdu interfluve area.

I.B. Mamontova, who studied spore–pollen assemblages from three prospect holes, referred them to the upper Miocene. All the assemblages are rich in pollen of dark conifers (mostly Pinaceae). However, they

are not identical in other features and may exemplify different levels of the upper Miocene.

I assume that palynospectra of clays from the prospect hole 112[a], or PA_{12} as I indicate them in this work, are older than others (prospect holes 106[a] and 113). They are rather diverse in the taxonomic aspect and show a significant proportion (13–20%) of Taxodiaceae (*Taxodium, Glyptostrobus*, and *Sciadopitys*), which associate with dominant Pinaceae represented by *Picea* sp. (10–15%), *Tsuga* sp. (15–16%), *Abies* (4–5%), *Pinus* s/g *Haploxylon* (3–6%), and *P.* s/g *Diploxylon* (6–10%). This assemblage also includes single pollen grains of *Podocarpus* sp., *Larix* sp., *Cedrus* sp., and *Ephedra* sp.

Significant angiosperms of the assemblage are Betulaceae (15–18%) and Juglandaceae: *Betula* sp. (10%), *Alnus* sp. (4–5%), *Corylus* sp. (1–2%), *Carpinus* sp. (1%), *Juglans* sp. (1–5%), *Carya* sp. (1–4%), and *Pterocarya* (1%). These taxa coexist with *Salix* sp., *Myrica* sp., *Quercus* sp., *Castanea* sp., *Ulmus* sp., *Liquidambar* sp., *Ilex* sp., *Rhus* sp., and *Sterculia* sp., exemplified by single pollen grains.

Herbaceous and sporiferous taxa are insignificant components of PA_{12}.

In its generic composition marked by a rather high percentage of Taxodiaceae, and due to the predominance of Betulaceae and Juglandaceae among angiosperms, PA_{12} is similar to PA_{10}. Nonetheless, it differs from the latter in having less diverse species of *Tsuga, Pinus,* and *Juglans* genera and by the insignificant proportion of *Carpinus* pollen.

In general, PA_{12} illustrates the coniferous–foliaceous forest vegetation of the temperate climatic zone. This vegetation resembles that of the early Miocene climatic optimum, although the latter is more diverse.

I consider PA_{12} as an assemblage of the short warming episode that took place close to the middle–upper Miocene boundary. Such an episode is recorded in the composition of marine fossils of the Pacific coastal zone (Gladenkov and Shantser, 1989).

I also think that spores and pollen from prospect hole 106[a] correspond to a higher stratigraphic level of the upper Miocene. Pollen of conifers is extremely abundant here and represents more than 80% of the assemblage. Dark conifers *Picea* sp. (28%), *Tsuga* sp. (12%), and *Abies* sp. (10%) are dominant in this group, whereas light conifers *Pinus* s/g *Haploxylon* (7%) and *P.* s/g *Diploxylon* (8%) are less abundant. Taxodiaceae (mainly *Taxodium* sp.) are also significant components of the pollen spectra in question, and their content can be as high as 16%. Angiosperms are extremely impoverished here. Their arboreal forms, whose abundance is steadily below 1%, are represented by *Juglans* sp., *Carya* sp., *Quercus* sp., *Ulmus* sp., *Acer* sp., and *Sterculia* sp. At the same time, nonabundant sporiferous and herbaceous plants are more diverse than in PA_{12}, being exemplified by *Sphagnum* sp. (1%), Polypodiaceae (7%), Ericaceae (1.5%), *Sparganium* sp. (0.5%), Gramineae (0.5%), *Thalictrum* sp. (0.5%), Cruciferae (1%), Umbelliferae (0.5%), and Convolvulaceae (0.5%). This assemblage from prospect hole 106[a] as a whole corresponds to a dark coniferous forest with accessory pines and sporadic broad-leaved trees.

Among the pollen assemblages distinguished by Mamontova, that of prospect hole 113 is the least diverse and seems to mark the highest stratigraphic level. It includes conifers and angiosperms in approximately equal proportions. Dominant taxa of dark conifers are *Picea* sp. (14%), *Tsuga* sp. (12%), and *Abies* sp. (1.5%), whereas another main group of Betulaceae is represented by *Alnus* sp. (10%), *Betula* sp. (10%), *Corylus* sp. (1.5%), and *Carpinus* sp. (1.5%). In addition, this level yielded two taxa of Juglandaceae: *Juglans* sp. (3.5%) and *Carya* sp. (4%). However, Taxodiaceae are almost missing here. Taxa of accessory types (0.5–1.5%) are *Podocarpus* sp., *Pinus* sp., *P.* s/g *Haploxylon*, *P.* s/g *Diploxylon*, *Larix* sp., and *Glyptostrobus* sp. in the group of conifers and *Myrica* sp., *Ulmus* sp., and *Liquidambar* sp. among angiosperms. Herbs and sporiferous plants again play an insignificant role in this assemblage, although they are somewhat more diverse than below, and two herbaceous groups even display a noticeable abundance: Cyperaceae (4%) and Gramineae (3%).

The last spore–pollen assemblage characterizes the community of dark conifers and small-leaved plants.

The entire succession of Miocene pollen assemblages from the Khogdu–Sivoi interfluve area manifests changes in vegetal communities induced by the progressing deterioration of the climate. As a result, the initially quite diverse coniferous–foliaceous forests were replaced first by dark coniferous vegetation and then by the impoverished community of dark conifers and small-leaved plants.

The conjoined stratigraphic interval of two upper palynospectra and PA_{12} presumably includes the uppermost portion of the middle Miocene and the greater part of its upper substage.

The upper Miocene beds are conventionally distinguished in the Khurmulin and Omogun depressions. In the first structure, this is a member of variegated clay and silt beds (15 m thick) resting on basalts overlying the upper coal-bearing sequence. In its lithology and position in the section, this member is correlative with the upper Miocene Golovino Formation of the adjacent Srednii Amur depression.

In the Omogun depression, the late Miocene age is accepted for the 12-m-thick member of clay enclosing an interbed of peat. This member underlies the Quaternary deposits and rests on the Omogun beds of the Eocene.

In the composite section of Paleogene-Miocene deposits of the Amgun–Gorin region, there are two intervals lacking palynological characteristics. The first of them comprises a greater part of the middle Miocene, and the next one corresponds to the topmost upper Miocene.

In a series of depressions, the middle Miocene interval is occupied by basalts overlying the upper coaliferous sequence. Outside these structures, basaltic extrusions can be even younger (early Miocene).

The terminal late Miocene (Messinian) was a period of severe cooling, but this event is not recorded in palynofloras of the Amgun–Gorin region. It is not inconceivable that we have here the respective hiatus in sedimentation separating two aforementioned geological megacycles.

Using the results of palynological studies, I classified the intervals of pollen assemblages described above as respective local biostratigraphic units in the ranks of floral beds (see table). Of course, their position in the standard stratigraphic scale is somewhat uncertain. However, despite this suspicion, some of them, especially the beds corresponding to extreme climatic events and bearing characteristic taxa, can be used as reference horizons in various correlations.

To conclude the discussion, I would like to note that, despite the terrestrial origin and restricted distribution areas of Paleogene–Miocene deposits in the Amgun–Gorin region, they are well correlative with coeval sediments in nearby areas of the Far East, Primor'e in particular. This may be a consequence of the uniform geological, biological, and climatic changes over the vast territory in question.

Reviewer M.A. Akhmet'ev

REFERENCES

Aleksandrova, A.N. and Kozyar, L.A., Paleobotanical Data Used to Subdivide Paleogene–Neogene Deposits in the Southwestern Siberian Platform, in *Paleogen i neogen Sibiri* (Paleogene and Neogene of Siberia), Novosibirsk: Nauka, 1978, pp. 136–149.

Baranova, Yu.N., Kartashova, G.G., and Konishchev, V.A., Continental Paleogene and Neogene in the North of Central Yakutia, in *Kontinental'nye tretichnye tolshchi Severo-Vostoka Azii* (Continental Tertiary Deposits in the Northeastern Asia), Novosibirsk: Nauka, 1979, pp. 7–21.

Baskakova, L.A., Coal-Bearing Deposits of the Orekhovka Depression in Primor'e: Lithology and Palynological Age Substantiation, *Tikhookean. Geol.*, 1990, no. 3, pp. 52–61.

Baskakova, L.A. and Gromova, N.S., Phytostratigraphic Subdivisions of Paleogene Deposits in the Southwestern Primor'e, *Sov. Geol.*, 1982, no. 11, pp. 68–78.

Brattseva, G.M. and Giterman, R.E., Spores and Pollen, in *Atlas fauny i flory neogenovykh otlozhenii Dal'nego Vostoka, Tochilinskii razrez Zapadnoi Kamchatki* (Atlas of Fauna and Flora from Neogene Deposits in the Far East: Tochilino Section in the Western Kamchatka), Moscow: Nauka, 1984, pp. 70–74.

Gladenkov, Yu.B. and Shantser, A.E., Stratigraphy and Correlation of Neogene Geological Events in Kamchatka, in *Kainozoi Dal'nego Vostoka* (Cenozoic of the Far East), Vladivostok: Biol.-Pochven. Inst. Akad. Nauk SSSR, 1989, pp. 168–175.

Gromova, N.S., Palynological Characteristics of the Coal-Bearing Deposits in the Cenozoic Rettikhovka Section (Southern Primor'e), in *Spory i pyl'tsa v otlozheniyakh fanerozoya* (Spores and Pollen from Phanerozoic Deposits), Leningrad: Vses. Geol. Inst., 1984, pp. 94–101.

Krasheninnikov, V.A., Serova, M.Ya., and Basov, I.A., Paleogene Zonation of Planktonic Foraminifers and Its Significance for the Paleogene Stratigraphic Scheme of the Pacific Region in High Latitudes, in *Kainozoi Dal'nego Vostoka* (Cenozoic of the Far East), Vladivostok: Biol.-Pochven. Inst. Akad. Nauk SSSR, 1989, pp. 4–21.

Kul'kova, I.A. and Volkova, V.S., Floral Assemblages at the Eocene–Oligocene and Early Miocene Boundaries in West Siberia, *Stratigr. Geol. Korrelyatsiya*, 1994, vol. 2, no. 3, pp. 107–112.

Laukhin, S.A. and Kul'kova, I.A., The Problem of Eocene–Oligocene Boundary in Central Siberia, in *Paleogen i neogen Sibiri* (Paleogene and Neogene of Siberia), Novosibirsk: Nauka, 1978, pp. 74–82.

Lukashova, L.I. and Mal'tseva, G.S., Eocene–Oligocene Deposits of the Evoron–Chukchagir Depression in the Lower Amur River Area (Palynological Data), in *Materialy po stratigrafii i paleogeografii Vostoka Asii i Tikhogo okeana* (Materials on Stratigraphy and Paleogeography of the Eastern Asia and Pacific Ocean), Vladivostok: Dal'nevost. Tsentr Akad. Nauk SSSR, 1987, pp. 35–42.

Paleogen i neogen Severo-Vostoka SSSR (Paleogene and Neogene of the Northwestern USSR), Yakutsk: Yakut. Nauchn. Tsentr Sib. Otd. Akad. Nauk SSSR, 1989.

Panova, L.A., *Oligotsen Zapadno-Sibirskoi nizmennosti* (Oligocene of the West Siberian Lowland), Moscow: Nauka, 1971, no. 135, pp. 40–50.

Panova, L.A., Gromova, N.S., and Maligonova, E.Yu., Palynostratigraphy of Paleogene Deposits, in *Prakticheskaya palinostratigrafiya* (Practical Palynostratigraphy), Leningrad: Nedra, 1990, pp. 149–182.

Zhezhel', O.N., Zamoruev, V.V., Sukhova, G.A., and Tsvetkov, V.P., Abstracts of Papers, *IV Dal'nevostochnoe regional'noe mezhvedomstvennoe stratigraficheskoe soveshchanie* (IV Far East Regional Interdepartmental Conference on Stratigraphy), Khabarovsk: Mezhved. Stratigr. Kom., 1990, pp. 268–270.

Stratigraphy and Geological Correlation, Vol. 5, No. 6, 1997, pp. 584–592. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 5, No. 6, 1997, pp. 64–72.
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Relations between Middle Miocene Basins of the Western and Eastern Paratethys

I. A. Goncharova and L. B. Il'ina

Paleontological Institute, Russian Academy of Sciences, ul. Profsoyuznaya 123, Moscow, 117647 Russia

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Abstract—The composition of mollusks from the hole near the town of Anan'ev (Ukraine) has been analyzed. The green sand and clay beds, which in Moldavia and Western Ukraine (Podolia) are referred to as the Podolian Formation, do not always correspond to the lower Badenian. The available data do not suggest any relationship between the Western and Eastern Paratethys in the early Badenian–Tshokrakian time. A connection between the two basins mainly occurred at the end of the late Badenian–Konkian period.

Key words: *middle Miocene, Podolian Formation, Badenian, Tshokrakian, Konkian, mollusks, Western Paratethys, Eastern Paratethys.*

In western Eurasia, a system of epicontinental seas (Paratethys) continued to exist in the Miocene, extending along the northern margin of the Tethys (Nevesskaya *et al.*, 1984). At the beginning of the Miocene, the connection of the Paratethys with the northern basin discontinued, and the climate, hydrology, and character of fauna were mainly controlled by its relations with the Mediterranean and, probably, Indo–Pacific parts of the Tethys, and by the degree of fauna exchange within the Paratethys proper (between its western and eastern parts).

In the middle Miocene (pre-Sarmatian time), basins of the Western and Eastern Paratethys were, for the most part, separated from each other. At the same time, the Eastern and Western Paratethys either remained essentially marine basins replenished with oceanic water (the early Badenian–early Tshokrakian and late Badenian–Konkian intervals) or were completely closed displaying a decrease or increase in salinity (in the late Badenian (Velichki Beds)) late Tshokrakian, and Karaganian periods) (*Istoriya ...*, 1986; Goncharova, 1989).

In the Sarmatian time, the Western and Eastern Paratethys basins were united. However, since the hydrology of the Sarmatian Sea is a controversial problem and needs to be additionally discussed, we shall not dwell on it in the current article.

More detailed relations between the Western and Eastern Paratethys in the middle Miocene, apart from the Sarmatian, in the zone of their contact (southeastern Romania, Moldavia, and southwestern Ukraine) are not quite clear, but are supposed to be as follows. At the beginning of the middle Miocene (early Badenian), the Western Paratethys Sea on the east reached the village of Lipkany, which is situated on the extreme northwest of Moldavia (the Bogorodchany Formation, Roshka *et al.*, 1968; Roshka and Khubka, 1981), and extended up to the Prut River in Romania (the Dezh tuffs; see Popescu, 1987).[1] The Tshokrakian deposits of the Eastern Paratethys, which are referred to the early Badenian, are recorded only much farther to the southeast, at the Golitsyn elevation of the Black Sea shelf (Kulichenko and Savron, 1984), and they might have extended to the southernmost part of the Sarat area in the southwest of the Odessa district (Roshka and Hubka, 1981). The early Badenian and Tshokrakian faunas are characteristic of the corresponding basins and do not show any evidence of intermixing (Goncharova, 1989).

At the next (lowermost upper Badenian–Karaganian stage, (*Stratigrafiya SSSR*, 1986), the Western Paratethys deposits were represented by the Tiras Formation and, just like the Bogorodchany deposits, were not recognized southeast of the village of Lipkany. The nearest outcrops of the Karaganian beds (the Eastern Paratethys) were observed only in the south of the Belgorod–Dniester region of the Ukraine near the villages of Polevoe and Shirokoe (Roshka *et al.*, 1968). These deposits do not contain mixed faunal assemblages either.

Finally, sediments of the Chernovtsy Formation that reach the village of Naslavche in the east (northern Moldavia), were formed in the considered territory of the Western Paratethys at the late Badenian–Konkian time. The boundary of this formation follows along the Kainar River, attaining its mouth, and then turns northeasterly towards the village of Kamenka situated at the Dniester River. Farther to the south, it runs along the

[1] F. Marinescu and his colleagues reconstructed a strait of the early Badenian sea that extended from the Danube lower stream towards the Black Sea (*Neogene Palaeogeographic ...*, 1988). However, the factual basis of this suggestion is unknown.

Dniester River up to the village of Tsybulevka and then turns southwest towards villages of Strasheny, Kotovsk, and Komrat. In southern Moldavia, this boundary is situated to the north of the town of Kagul and continues into Romania (Roshka, 1969). The Konkian deposits of the Eastern Paratethys are recorded in natural outcrops traceable from east to west almost up to Odessa. Both the upper Badenian and Konkian deposits comprise faunal assemblages typical of the respective basins (*Stratigrafiya SSSR*, 1986).

Thus, the most significant data for paleogeographic reconstructions of interrelations between the Eastern and Western Paratethys during the considered period (from the middle Miocene to the Sarmatian) are those that reflect events in the territory of Moldavia and southwestern Ukraine, that is, in the areas separating the nearest outcrops of the two basins.

Toward the northeast from the most southeastern outcrops of the Bogorodchany and Tiras formations in the Dniestr area of Podolia (Ukraine), there is an exposed sequence of greenish clayey sand, kaolin-bearing sandstone, slightly calcareous sticky ceramic clay, and carbonaceous clay containing siliceous pebbles of the underlying rocks in its lower part. The thickness of the deposits is 3–10 m and rarely exceeds 20 m. Their distribution area is about 10 000 km^2 (Vyrzhikovskii, 1929; Molyavko, 1982). Outcrops of these deposits are traceable along the Tyrnava River and to the southeast of the town of Yarmolintsy (village of Sutkovtsy) across the basins of the left tributaries of the Dniester River, the Studenitsy River and synonymous village, the Ushitsy River (villages of Zin'kov, Sinyakovtsy, Velikaya Kuzheleva, Min'kovtsy, and Timkov), and the Kalyus River (villages of Berezovka, Kalyus, Kalyusik, and Kucha). Farther to the east, the deposits in question are exposed along the left bank of the Dniester River (Nagoryany, Rovnoe, Ozarintsy, Mogilev-Podol'skii, Chernevtsy, Vily Yarutskie, Yaruga, Yampol, Velikaya Kosnitsa, and Stena localities), and then they form an easterly protruding tongue near the village of Tomashpol. In Moldavia (villages of Grushka, Kuz'min, and Kamenka), these outcrops are quite rare, and in the south they are restricted to surroundings of the town of Rashkov (Vyrzhikovskii, 1929; Sorochan, 1958). These green sands and clays overlie the Cretaceous or more ancient rocks. The deposits are either transgressively overlain with clear signs of erosion by the fauna-bearing upper Badenian rocks (analogous to the Chernovtsy beds) or grade into the lower Sarmatian deposits (Sorochan, 1958; Molyavko, 1969; Roshka, 1975). The deposits have a low carbonate content and are virtually devoid of organic remains. They contain (Rutkovtsy and Min'kovtsy localities of the Khmel'nitskii region) scarce poorly preserved foraminifers *Ammonia* cf. *galiciana* (Putrja), *A.* cf. *beccarii* (L.), *Cibicides* sp., *Quinqueloculina* sp., and *Elphidium* sp., associated with spicules and sterrasters of sponges. Because these fossils are poorly preserved, one cannot be sure of their occurrence *in situ* (Venglinskii and Goretskii, 1979). Vyrzhikovskii (1929) referred these deposits to the "Podolian Stage" or, to put it more precisely, to the Podolian Formation. Contrary to the opinion of certain researchers (Molyavko, 1982), the only well-preserved molluscan fauna of *Anadara turonica* (Duj.), *Linga columbella* (Lmk), *Loripes dentatus* (Defr.), *Parvicardium papillosum* (Poli), *Turritella bicarinata* Eichw., and *Dentalium* sp., which are described by Dumitrashko (1929) from the deposits near the village of Kuchi (the Kalyus River), comes, as believed by V.Kh. Roshko, from the overlapping upper Badenian deposits, rather than from the Podolian Formation.

Green and greenish gray unstratified sandy clays and volcanic bentonites intercalated with poorly sorted quartz sand and cloddy sandy clay were recovered by boreholes south and east of the aforementioned series of green rock outcrops in the territory of Moldavia and Ukraine (within an area extending up to the Kotovskaya railway station and the town of Anan'ev in the east and down to the Black Sea coast of Moldavia and Ukraine in the south). In their lithology, these rocks are indistinguishable from the green deposits and are either referred to as the Podolian Formation (Roshka, 1973; Roshka and Khubka, 1981) or assigned to the regional Tshokrakian stage with the same degree of conventionality (Roshka *et al.*, 1968; Roshka, 1969). In central areas of Moldavia, northwest of Chisinau (villages of Korneshty and Balaneshty), these deposits are correlative with the Bogorodchany Formation of the Moravian Substage of the Badenian Stage, because they contain Badenian mollusks and nannoplankton including *Sphenolithus heteromorphus* characteristic of Zone NN 5. (Golovina *et al.*, 1986). The presented evidence suggests that a bay of the early Badenian sea existed here (Fig. 1). Chumakov *et al.* (1992) proposed a similar correlation between the green sandy bentonitic clays of volcanic origin from the Podolian Formation (eastern Moldavia), the Dej Tuff (Romania), and the tuff horizon of the Bogorodchany Formation in the Cis-Carpathian province. Unfortunately, they have not precisely indicated the area of their research.

Green-gray glauconite-containing silty clays and clayey silts with lower Miocene microfauna were recovered by boreholes in the southwestern part of the Odessa district within the Dniester–Danube interfluve area near the villages of Novoselovka, Vishnevoe, and Yaroslavka (Roshka and Khubka, 1981). These beds are overlain by lithologically similar rocks penetrated by boreholes near the villages of Yaroslavka and Vishnevoe, where they bear mollusks and microfauna. Based on finds of *Chlamys varnensis* (Toula) (= *Ch. pertinax* Zhizh.) and *Ervilia praepodolica* Andrus, Roshka and Khubka (1981) attributed this fauna to the Tshokrakian. However, *Textularia* sp. discovered in the same deposits is unknown in the Eastern Paratethys higher than the base of the upper Tarkhanian and does not allow us to regard this dating as undoubtedly true. Moreover, we cannot exclude that the Tshokrakian basin might have reached this region on the west. The drilling results

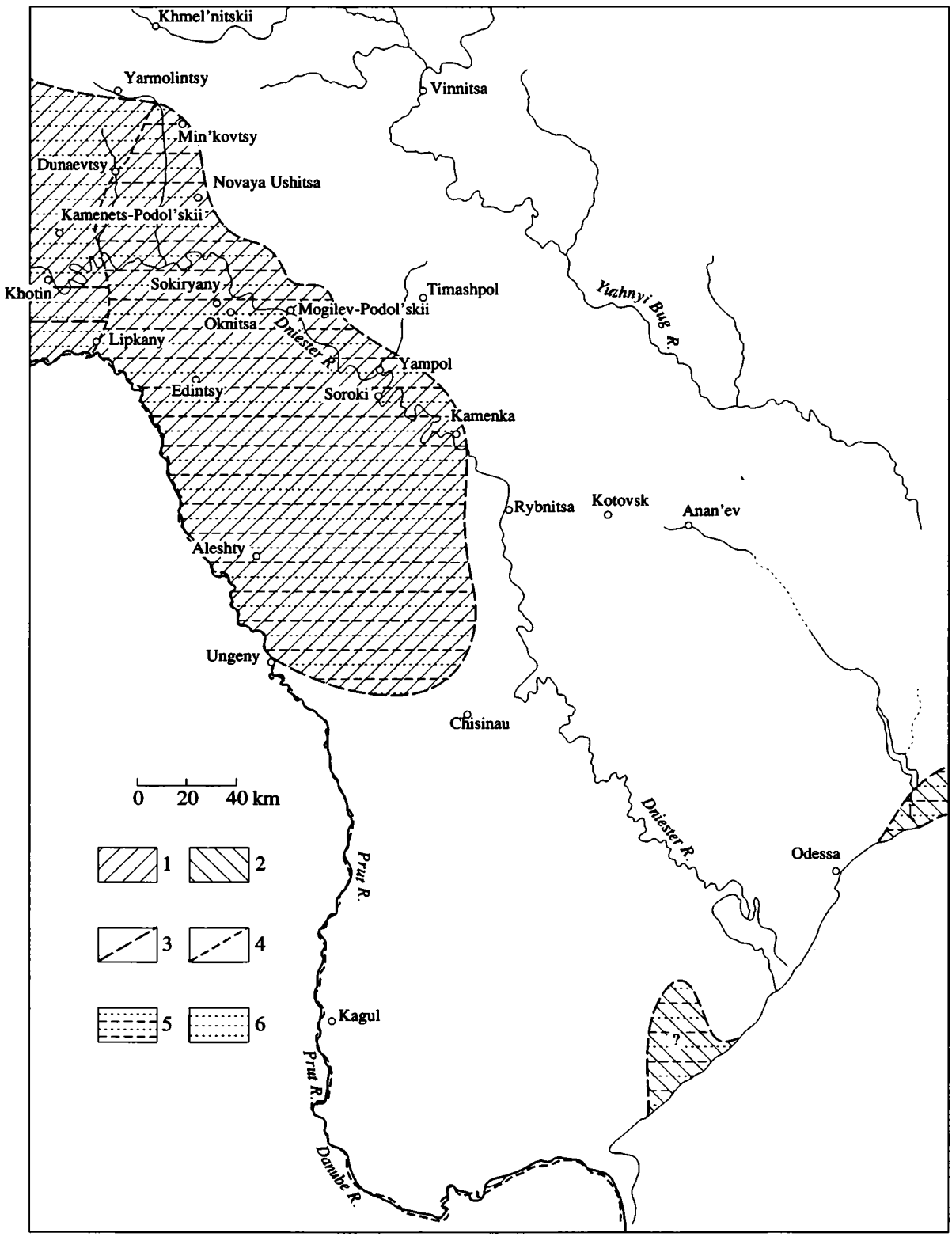


Fig. 1. Paleogeography of the contiguous early Badenian and Tshokrakian basins: (1) Western Paratethys, (2) Eastern Paratethys, (3) conventional boundary of the basin, (4) boundary between lithofacies, (5) sandy–clayey deposits, (6) sand.

suggest that the green thin (~5.5 m) deposits are, in general, widespread in this part of the Odessa district (the Belgorod-Dniester, Sarat, Artsiz, and Tatarbunar areas after Roshka *et al.*, 1968). No other contacts with the underlying rocks, except those penetrated by the boreholes, have been established, though the recovered fauna suggest that their age is no younger than the initial late Tarkhanian (Goncharova, 1989). The greenish gray clayey limestone and gray-green sandy clay up to 6.5 m thick, which were penetrated by boreholes in the vicinity of the villages of Shirokoe and Polevoe of the Belgorod–Dniester region, occupy a higher stratigraphic position. They contain the Karaganian fauna. These are mollusks *Spaniodontella pulchella* (Baily), *S. gentilis* (Eichw.), *Ervilia pusilla* Phil., *Barnea* ex gr. *pseudoustjurtensis* Bog., and *Potamides nodosoplicatus* (M. Hoern.), whereas among foraminifers there are specimens of *Nonionella karaganica* Krasch. (Roshka, 1969).

In the northeastern and central areas of Moldavia mentioned above, the green-colored lower Badenian sequence is transgressively overlain with a stratigraphic disconformity by the upper Badenian deposits (the Chernovtsy Formation). In the Prut-surrounding areas of northern and central Moldavia, within the reef zone, the Chernovtsy Formation of the Kosovian Substage is represented in its basal part by organogenic–clastic limestones (about 8 m thick) sometimes intercalated with subordinate interlayers of clays and sanstones; higher, it contains clayey Lithothamnium (up to 20 m thick) or Vermetus–Lithothamnium limestone bioherms (some of them are up to 60 m high). East of the reef belt, the Chernovtsy deposits are universally represented by organogenic limestones, sanstones, and sands with clay interlayers. The role of limestones in the section declines from west to east. Usually, the thickness of the entire formation in these areas decreases, not exceeding 44 m (Roshka and Khubka, 1981; *Stratigrafiya SSSR*, 1986). It is a common opinion that the distribution area of the Chernovtsy Formation is much less than that of the Podolian Formation (Roshka and Khubka, 1981). This is not necessarily the case, particularly in the east, where the deposits of the Podolian and Chernovtsy formations are identical in lithology and consist of similar greenish gray sands in both cases. The deposits in the vicinity of the town of Anan'ev are a good example. The rocks recovered by drill holes here are commonly attributed to the Podolian Formation, though in some cases they are interpreted as Tshokrakian in age.

M. Bargu and his colleagues, who studied microfauna from certain boreholes in the northern part of the Odessa district (Balta, Kotovsk, Lyubashev, and Anan'ev localities), identified here the upper Badenian ("upper Tortonian") rocks, which may be considered as analogues to the Chernovtsy Formation (Gil'kman *et al.*, 1981). This conclusion of Ukrainian researchers is consistent with the new data that we obtained by analyzing mollusks from core samples of Hole 11 drilled in 1982 during the geological survey at the scale 1 : 200 000 near the town of Anan'ev. The samples with molluscan shells of different degrees of preservation was kindly submitted by Roshka for our study. We take this occasion to express our gratitude to him.

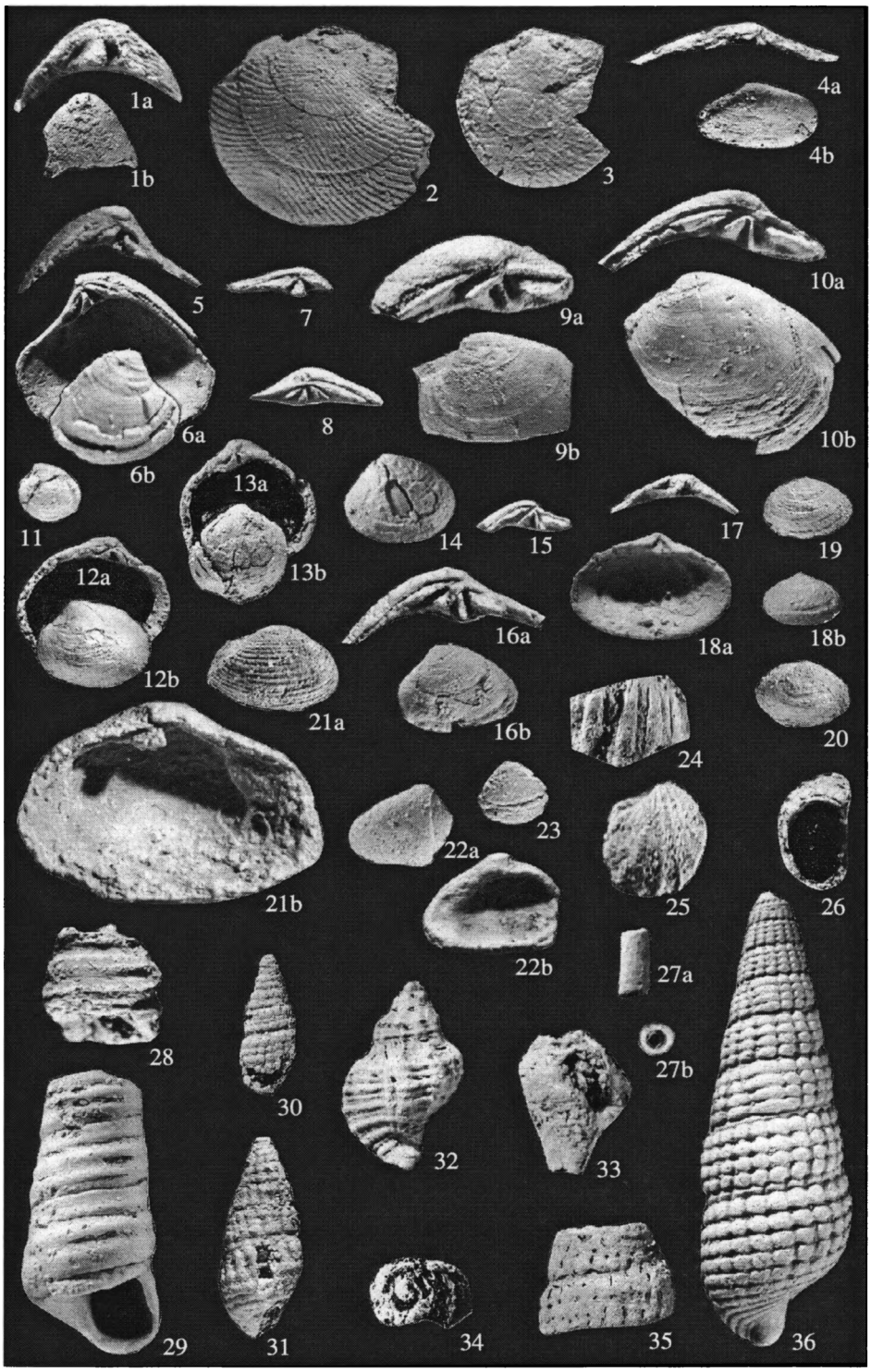
The 4.5-m-thick bed of greenish gray clayey consolidated quartz sands, ranging from coarse- to medium-grained and enclosing interlayers of sandstone and bentonite clay, was recovered from Hole 11 at a depth of 105–109.5 m. According to Roshka, these deposits are of the Tshokrakian age; they rest on the Upper Cretaceous limestones and underlie the lower Sarmatian rocks.

In these deposits from Hole 11, we have identified 15 molluscan species; we also succeeded in identifying 7 more specimens at the genus or subgenus levels. *Spondylus* sp. (Plate, Fig. 1) is represented by an upper fragment of the shell with a well-preserved hinge. There are three incomplete shells of a lucinid form *Divalinga ornata* (Agassiz) (Plate, Figs. 2, 3). Three well-preserved Veneridae shells belong to *Clausinella basteroti* (Deshayes) (Plate, Figs. 5, 6) and six to *Pitar* (*Pitar*) *rudis* (Poli) (Plate, Figs. 14–16); two fragments of *Callista italica* (Defrance) among them are represented by the beak parts with the hinge (Plate, Figs. 9, 10); six shells are those of *Timoclea* (*Parvivenus*) *marginata* (Hoernes) (Plate, Figs. 11–13); and a couple of fragments of the right valves with the hinge exemplify *Paphia* (Callistotapes) sp. (Plate, Fig. 8) and *Venerupis* (*Polititapes*) sp. (Plate, Fig. 7). We have identified one well-preserved right valve of *Tellina* (*Laciolina*) *pretiosa* Eichwald among tellids (Plate, Fig. 4). Mesodesmatids include ten identified shells of *Ervillia pusilla pusilla* (Philippi) (Plate, Figs. 17–20). Corbulids are represented by three shells of *Corbula* (*Caryocorbula*) *carinata* Dujardin (Plate, Fig. 21), by a fragment of the left valve of *C.* (*Caryocorbula*) sp. (Plate, Fig. 22), and by two shells of *C.* (*Varicorbula*) *gibba gibba* (Olivi) (Plate, Fig. 23). Cardiids are represented by a shell and a shell fragment of *Acanthocardia* sp. with poorly preserved ornamentation (Plate, Figs. 24, 25). A single shell of *Chama* (*Psilopus*) *gryphoides* Linné was also recorded (Plate, Fig. 26).

Gastropods are exemplified by isolated shells and shell fragments, so that it was not always possible to distinguish between closely related species. The fragmentary ornamentation of *Turritella* cf. *tricincta* (Plate, Fig. 28) appeared to be similar to that of *T. tricincta* Borson (Plate, Fig. 29), known to occur in the Miocene of the Western Paratethys and in the Tarkhanian of central Cis-Caucasia. A fragment of *Terebralia* cf. *bidentata* (Plate, Fig. 35) from the group of potamids, also greatly resembles *T. bidentata* (Defrance in Grateloup) (Plate, Fig. 36) from the Konkian beds of the central Cis-Caucasia in its ornamentation. At the same time, *Potamides* (*Pirenella*) *gamlitzensis* (Hilber) (Plate, Fig. 30) and *P.* (*Pirenella*) *nodosoplicatus* (M.Hoernes) (Plate, Fig. 31) are identified without any doubt. We

managed to define *Natica* sp. (Plate, Fig. 34) only up to the genus category, just like *Hadriania* sp. among muricids (Plate, Fig. 33), whose last whorl and specific features of the fragmentary preserved ornamentation somewhat resemble the same elements of *H. boecki* (R. Hoernes et Auinger) (Plate, Fig. 32) known from the middle Miocene deposits of the Western and Eastern Paratethys.

Neither Konkian nor Tshokrakian endemics are present in the assemblage. The entire assemblage is of the Badenian aspect, but three species [*Pitar* (*Pitar*) rudis, *Corbula* (*Caryocorbula*) *carinata*, and *Turritella tricincta*], as well as the genus *Spondylus* and subgenus *Paphia* (*Callistotapes*), have not yet been encountered in synchronous deposits of the Eastern Paratethys. Five Badenian species [*Divalinga ornata, Tellina*



(*Laciolina*) *pretiosa, Potamides* (*Pirenella*) *gamlitzensis, Terebralia bidentata,* and *Dentalium* (*Antalis*) sp.] and representatives of the genus *Hadriania* are present in the Konkian, though not recorded in the Tshokrakian deposits. Other Badenian species also inhabited the Tshokrakian and Konkian basins; nearly one-third of them was found only in the southeast of the Eastern Paratethys. Since several molluscan specimens from Hole 11 are of late Badenian appearance (not older), we date the whole assemblage as corresponding to this interval. Such an interpretation is consistent with the microfaunal evidence published by Ukraininan researchers (Gul'kman *et al.,* 1981).

The late Badenian fauna discovered in the vicinity of the town of Anan'ev lacks the majority of the euryhaline Badenian species typical of the eastern and southeastern areas of the Konkian basin in the Sartaganian–late Veselyankian time (Trans-Caucasia and Trans-Caspian region). Therefore, we can definitely state that the late Badenian sea ended here with a bay, the salinity of which was somewhat lower than that of the main basin. Most likely, this was a continuation of the Rybnitsa Bay of the Chernovtsy sea (Roshka and Sayanov, 1965), which was not restricted in the east by the area adjacent to the Dniester River but continued farther east and reached the longitudinal mark between the villages of Lyubashevka and Vradievka. There is no reason to suggest any connection between the Western and Eastern Paratethys in these regions (Fig. 2).

The materials from boreholes drilled in the Dniester–Prut interfluve area south of Odessa may suggest possible links between the Western and Eastern Paratethys (Roshka *et al.,* 1968). In the aforementioned Sarat, Artsiz, and Tatarbunar areas, the green beds mainly corresponding to the upper part of the lower Miocene are overlapped by rocks similar in lithology to the Chernovtsy or correlative deposits. Their age cannot be unequivocally determined as the Konkian or late Badenian, since the respective fauna composition is of a mixed character. From these deposits, Roshka identified (in many cases with "cf." and "ex gr." remarks) many species of mollusks characteristic of both the late Badenian and Konkian or representing only Konkian endemics, such as *Acanthocardia andrussovi* (Sok.), *Obsoletiforma lithopodolica ruthenica* (Hilb.), *Loripes dentatus* (Desh.) [= *L. niveus* (Eichw.)], *Mactra basteroti* May., *Chlamys malvinae* (Dub.), *Ervilia pusilla trigonula* Sok., *Corbula gibba* Ol., *Parvivenus konkensis* (Sok.), *Clausinella basteroti* (Desh.), *Neritina picta* (Fer.), *Barnea ustjurtensis* (Eichw.), *Turritella spirata* (Brocchi) (= *T. subangulata* Eichw.), and several other species. In addition, he distinguished *Diloma* (*Paroxystele*) *orientalis* Cossm. et Peyr., *Scaphander lignaris* (L.), *Anadara turonica* (Duj.), *Neopycnodonte cochlear* (Poli), and others. This list enables us to attribute these mollusks to the mixed late Badenian–Konkian assemblage. The euryhaline species of foraminifers also identified here are *Borelis melo* (F. et M.), *Triloculina gibba* Orb., *Elphidium notabilis* Pischw., *E. macellum* (F. et M.), *Quinqueloculina consobrina* Orb., *Peneroplis laevigatus* Karr., *Pyrgo simplex* Orb., *Porosononion subgranosus* (Egger), *Ammonia beccarii* (L.), and some others (Roshka *et al.,* 1968). *Diloma* (*Paroxistele*) *orientalis*, typical of the Eastern Paratethys, has so far been encountered only in the Sartagan beds of the Trans-Caspian region and Trans-Caucasia, and, occasionally, in western Cis-Caucasia. Farther to

Plate. Late Badenian mollusks from Hole 11 in the vicinity of the town of Anan'ev (Odessa district, Ukraine)

(1) *Spondylus* sp, no. 583/937, the right valve: (1a) hinge (×3), (1b) external side (×1.5). (2, 3) *Divalinga ornata* (Agassiz) (×2): (2) no. 583/938, the shell sculpture, (3) no. 583/939, the right valve, external side. (4) *Tellina* (*Laciolina*) *pretiosa* Eichwald, no. 583/940, the right valve: (4a) hinge (×5), (4b) external (×1.5). (5, 6) *Clausinella besteroti* (Deshayes): (5) no. 583/941, the hinge of the left valve (×5); (6) no. 583/942, the right valve: (6a) internal side (×5); (6b) external side (×3). (7) *Venerupis* (*Polititapes*) sp., no. 583/943, the hinge of the right valve (×3). (8) *Paphia* (*Callistotapes*) sp., no. 583/944, the hinge of the right valve (×5). (9,10) *Callista italica* (Defrance), left valves, (9) 583/945: (9a) hinge (×2), (9b) external side (×1.5); (10) no. 583/946: (10a) hinge (×2), (10b) external side (×1.5). (11–13) *Timoclea* (*Parvivenus*) *marginata* (Hoernes): (11) no. 583/947, external side of the left valve (×2); (12) no. 583/948, the left valve: (12a) internal side (×3), (12b) external side (×2); (13) no. 583/949, the right valve: (13a) internal side (×4); (13b) external side (×2). (14–16) *Pitar* (*Pitar*) *rudis* (Poli), the left valves: (14) N583/950, external side (×3); (15) no. 583/951, hinge (×5); (16) no. 583/952: (16a) hinge (×5), (16b) external side (×3). (17–20) *Ervilia pusilla pusilla* (Philippi); (17) no. 583/953, a slightly damaged hinge of the right valve (×4); (18) no. 583/954, the left valve: (18a) internal side (×4), (18b) external side (×2); (19) no. 583/955, external side of the left valve (×2); (20) no. 583/956, the same (×2). (21) *Corbula* (*Caryocorbula*) *carinata* Dujardin, no. 583/957, the right valve: (a) external side (×2), (b) internal side (×4). (22) *Corbula* (*Caryocorbula*) sp., no. 583/958, a fragment of the left valve with strongly damaged outer surface: (a) external side (×2), (b) internal side (×3). (23) *Corbula* (*Varicorbula*) *gibba gibba* (Olivi), N 583/959, external side of the right valve, (×3). (24, 25) *Acanthocardia* sp., (24) no. 583/960, posterior side of the right valve (×4); (25) no. 583/961, a fragment of ornamentation (×2). (26) *Chama* (*Psilopus*) *gryphoides* L., no. 583/962, internal side of the left valve, (×3). (27) *Dentalium* (*Antalis*) sp., no. 583/963, a fragment of a shell (×3): (a) lateral side (b) cross section. (28) *Turritella* cf. *tricincta* Bors., no. 583/964 (×2), shell fragment. (29) *Turritella tricinata* Bors., no. 4450/63 (×1.5), the regional Tshokrakian Stage of central Cis-Caucasia, the Yaman-Djalga Ravine; the shell damaged near the aperture (redeposited from the Tarkhanian beds). (30) *Potamides* (*Pirenella*) *gamlitzensis* (Hilb.), no. 583/965 (×1.5), the shell side opposite the aperture. (31) *Potamides* (*Pirenella*) *nodosoplicatus* (M. Hoern.), no. 583/966 (×2), the shell side opposite the aperture. (32) *Hadriania boeckhi* (R.Hoern. et Auing.), no. 4450/290 (×2), the regional Konkian Stage of Mangyshlak, Mt. Aksengir; the shell side opposite to the aperture. (33) *Hadriania* sp., no. 583/967 (×6), damaged body whorl as sideed from the side opposite to the aperture. (34) *Natica* sp., no. 583/968 (×3), a shell fragment from the apical side. (35) *Terebralia* cf. *bidentata* (Defr. in Grat.), no. 583/969 (×3), a shell fragment. (36) *Terebralia bidentata* (Defr. in Grat.), no. 4450/209 (×1.5), the regional Konkian Stage of central Cis-Caucasia, Mt. Dubrovaya; the shell side opposite the aperture.

Collections no. 583 and no. 4450 is stored at the Paleontological Institute, Russian Academy of Sciences.

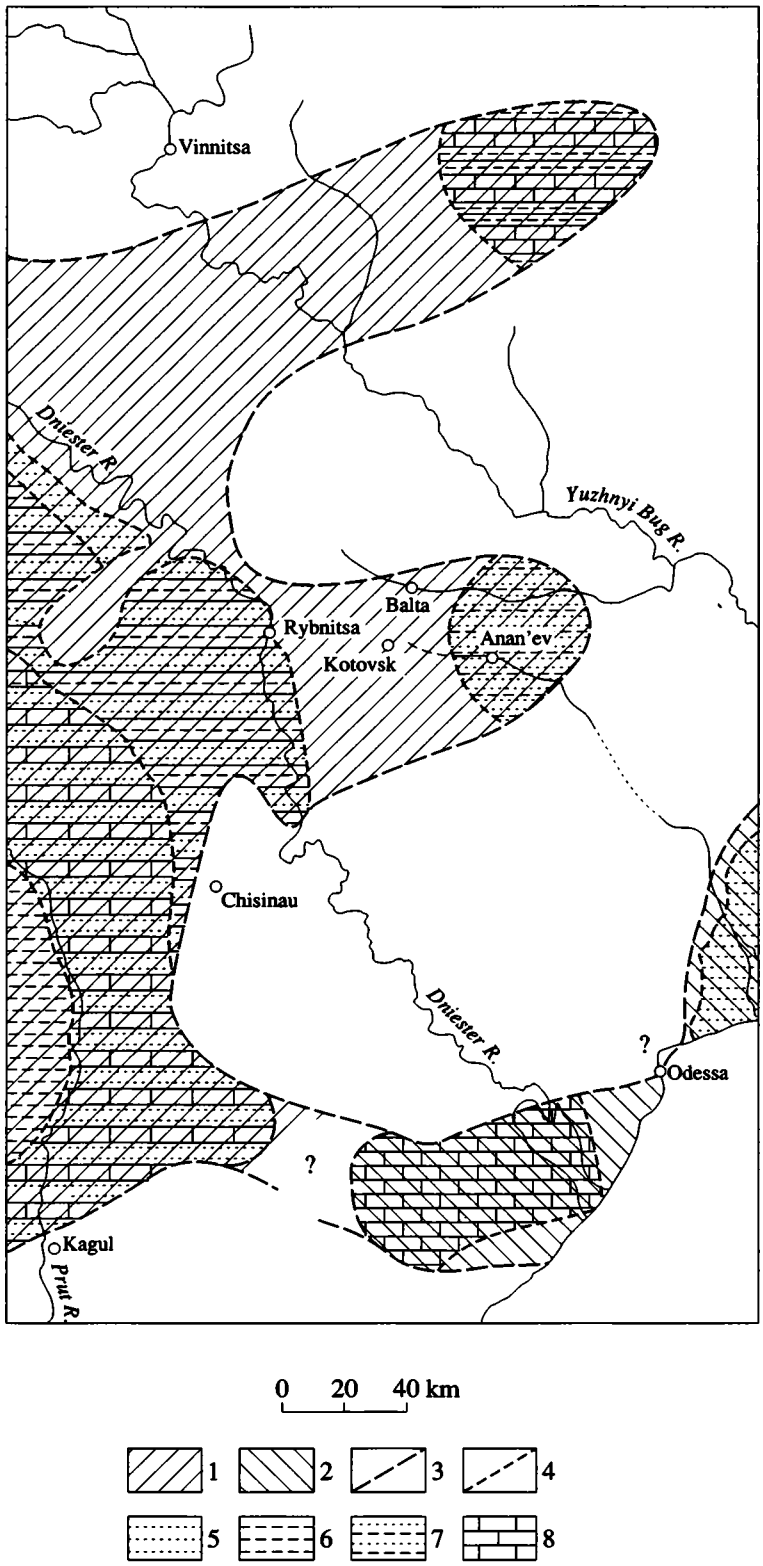


Fig. 2. Paleogeography of the contiguous Badenian and Konkian basins. (1) Western Paratethys, (2) Eastern Paratethys, (3) conventional boundary of the basin, (4) boundary between lithofacies, (5) sand, (6) clay or silt, (7) sandy–clayey deposits, (8) organogenic limestone.

the west, in the Crimea and southern Ukraine, this species has not been recorded, though it is quite common in the late Badenian beds of the Western Paratethys. *Turritella* species known from the Konkian strata of the Eastern Paratethys were characteristic mostly of the late Veselyanka time, that is, of the second prochoresis of the marine, more or less, euryhaline fauna into the Konkian basin (Il'ina, 1993).

In the late Badenian–Konkian period, the Western and Eastern Paratethys may have been linked through the Dobrudzha and Birladian troughs, and farther, through the southern provinces of the present Odessa district (Roshka *et al.*, 1968; Didkovskii and Nosovskii, 1975) (Fig. 2). However, these links most likely appeared at the end of the late Veselyanka time, rather than at the Sartaganian Stage, since the mentioned molluscan assemblage from the Dniester–Prut interfluve area contains Veselyankan endemics in addition to euryhaline species. In general, both in the Sartaganian and Veselyankan times, the Konkian basin was connected with an open sea in the southest of the basin, which is confirmed by the occurrence of diverse euryhaline mollusks in the Trans-Caucasian, Trans-Caspian, and Cis-Caucasian regions (Il'ina, 1993, 1995).

CONCLUSION

(1) The available data suggest that there was no connection between the early Badenian and Tshokrakian basins.

(2) The communication between the late Badenian and Konkian basins was, most likely, through the Dniester–Prut interfluve area; this communication existed in the late Veselyankan time.

(3) The age of mollusks from Hole 11 near the town of Anan'ev is assessed as the late Badenian.

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Reviewer I.A. Basov

REFERENCES

Chumakov, I.S., Byzova, S.L., and Ganzei, S.S., *Geokhronologiya i korrelyatsiya pozdnego kainozoya Paratetisa* (Geochronology and Correlation of the Late Cenozoic in the Paratethys), Moscow: Nauka, 1992.

Didkovs'kii, V.Ya. and Nosovs'kii, M.F., The Black Sea Depression: Miocene, in *Stratigrafiya URSR. Neogen* (Stratigraphy of the UkrSSR: Neogene), Kiev: Naukova Dumka, 1975, vol. 10, pp. 32–70.

Dumitrashko, N.V., Fauna from the Mediterranean Deposits near the Village of Kucha, the Kam'yanech Region, *Visnik UVGK*, 1929, no. 13, pp. 2–32.

Gil'kman, A.I., Savenko, N.G., and Barg, I.M., The Problem of Discriminating the "Upper Tortonian" Deposits in Northern Areas of the Odessa Region, *Geol. Zhurn*, 1981, vol. 41, no. 4, pp. 136–140.

Golovina, L.A., Muzylev, N.G., and Roshka, V.Kh., New Data on Stratigraphy of the Badenian Deposits in Moldavia, in *Paleontologo-stratigraficheskie issledovaniya razrezov mezozoya i kainozoya mezhdurech'ya Dnestr–Prut* (Paleontologic and Stratigraphic Studies of the Mesozoic and Cenozoic Sequences in the Dniester–Prut Interfluve Region), Kishinev: Shtiintsa, 1986, pp. 24–34.

Goncharova, I.A., *Dvustvorchatye mollyuski tarkhanskogo i chokrakskogo basseinov* (Bivalve Mollusks of the Tarkhanian and Tshokrakian Basins), Moscow: Nauka, 1989.

Il'ina, L.B., *Opredelitel' morskikh srednemiotsenovykh gastropod Yugo-Zapadnoi Evrazii* (Guide to the Middle Miocene Marine Gastropods from the Southwestern Eurasia), Moscow: Nauka, 1993.

Il'ina, L.B., Relations between the Middle Miocene (Tarkhanian–Konkian) Basins of the Eastern Paratethys and Adjacent Seas, in *Ekosistemnye perestroiki i evolyutsiya biosfery*, Moscow: Paleontol. Inst. Ross. Akad. Nauk, 1995, no. 2, pp. 133–136.

Istoriya neogenovykh mollyuskov Paratetisa (History of Neogene Mollusks in the Paratethys), Moscow: Nauka, 1986.

Kulichenko, V.G. and Savron', E.B., The Middle Miocene, in *Geologiya shel'fa USSR, Stratigrafiya (shel'f i poberezh'e Chernogo morya)* [Shelf Geology of the USSR, Stratigraphy (Shelf and Coast of the Black Sea)], Kiev: Naukova dumka, 1984, pp. 123–130.

Molyavko, G.I., Disputable Problems of the Neogene Stratigraphy in Ukraine and Moldavia, in *Stratigrafiya neogena Moldavii i yuga Ukrainy* (The Neogene Stratigraphy of Moldavia and Southern Ukraine), Kishinev: Akad. Nauk MoldSSR, 1969, pp. 3–12.

Molyavko, G.I., The Podolian Formation, in *Stratigraficheskii slovar'* (Glossary of Stratigraphy), Leningrad: Nedra, 1982, p. 343.

Neogene Palaeogeographic Atlas of Central and Eastern Europe, Budapest: Hung. Geolog. Inst. Map, 1988, no. 3.

Nevesskaya, L.A., Voronina, A.A., Goncharova, I.A., *et al.*, History of the Paratethys, in *Paleookeanologiya. Kollokvium 03. Doklady. K XXVII Mezhdunar. geol. kongressu* (Paleooceanology, Colloquium 03, Proc. 27 Int. Geol. Congr.), Moscow: Nauka, 1984, vol. 3, pp. 91–101.

Popescu, G., Marine Middle Miocene Microbiostratigraphical Correlation in Central Paratethys, *Dări seama... Inst. Geol. Geofiz.*, 1987, vol. 72–73/3, pp. 149–167.

Roshka, V.Kh., The Neogene Stratigraphy of the Belgorod–Dniester Region, in *Stratigrafiya neogena Moldavii i yuga Ukrainy* (The Neogene Stratigraphy of Moldavia and Southern Ukraine), Kishinev: Akad. Nauk MoldSSR, 1969, pp. 91–105.

Roshka, V.Kh., Stratigraphy of the Neogene Deposits in the Kishinev Sity and Surroundings, in *Paleontologiya i stratigrafiya mezozoiskikh yuzhnykh okrain Russkoi platformy* (Paleontology and Stratigraphy of the Southern Meosozoic Margins of the Russian Platform), Kishinev: Shtiintsa, 1973, pp. 141–151.

Roshka, V.Kh., The Podolian Stage, in *Stratotipy yarusov neogena Sredizemnomor'ya* (Stratotypes of the Neogene Stages in the Mediterranean), Bratislava: Veda, 1975, vol. 2, p. 293.

Roshka, V.Kh. and Khubka, A.N., The Neogene Stratigraphy in the Dniester–Prut Interfluve Area, in *Biostratigrafiya antropogena i neogena yugo-zapada SSSR* (Anthropogene and Neogene Stratigraphy in the Southwestern USSR), Kishinev: Shtiintsa, 1981, pp. 78–106.

Roshka, V.Kh. and Sayanov, V.S., Middle Miocene: The Formation Time of the Podolia Formation, in *Paleogeografiya Moldavii* (Paleogeography of Moldavia), Chisinau: Kartya Moldovenyaske, 1965, pp. 95–97.

Roshka, V.Kh., Sinegub, V.V., Bobrinskaya, O.G., *et al.*, Middle Miocene Deposits in the Southern Part of the Prut–Dniester Interfluve Area, *Izv. Akad. Nauk MoldSSR, Ser. Biol. Khim. Nauk,* 1968, no. 3, pp. 50–56.

Sorochan, O.A., *Stratigrafiya srednemiotsenovykh vidkladiv Volino-Podil's'koi skhilu Ukrains'kogo kristalichnogo shchita za faunoyu peletsipod* (Stratigraphy of the Middle Miocene Deposits in the Volhynia–Podolia Uplift of the Ukrainian Crystalline Shield Based on the Pelecypod Fauna), Kiiv: Akad. Nauk UkrSSR, 1958.

Stratigrafiya SSSR. Neogenovaya sistema (Polutom 1) [Stratigraphy of the USSR. Neogene System (Semivolume 1)], Moscow: Nedra, 1986.

Venglinskii, I.V. and Goretskii, V.A., *Stratotipy miotsenovykh otlozhenii Volyno-Podol'skoi plity, Predkarpatskogo i Zakarpatskogo progibov* (Stratotypes of the Miocene Deposits in the Volhynia–Podolia Plate, and in the Cis- and Transcarpathian Depressions), Kiev: Naukova dumka, 1979.

Vyrzhikovskii, R.R., Notes on the "Podolian Stage" of the Neogene in the Dniester Region, *Izv. Geol. Komiteta,* 1929, vol. 48, no. 4, p. 126.

Stratigraphy and Geological Correlation, Vol. 5, No. 6, 1997, pp. 593–603. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 5, No. 6, 1997, pp. 73–84.
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On the memory of B.B. Nazarov

Ordovician Deposits of the Ganychalan Terrane (Penzhinskii Range of the Koryak Highland)

S. D. Sokolov*, V. N. Grigoriev*, V. A. Aristov*, N. L. Evglevskii, A. A. Peive*, and L. E. Shterenberg***

** Institute of Geology, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 109017 Russia*
*** North Kamchatka Complex Geological Expedition, Korf Settlement, Kamchatka district, 683000 Russia*

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Abstract—The volume of both original and published material on the fauna, composition, and facies types of the Ordovician deposits of Penzhinskii Range is summarized in this work. The deposits (the Elgeminai Group) represent a characteristic component of the Ganychalan Terrane, one of the basic structural units of the range. Five sections are considered, and three stratigraphic units are distinguished: the Khinantykul (Arenigian (?)–early Llanvirnian), Kuyulpil (Llanvirnian–early Caradocian), and Olenii (late Caradocian–Ashgillian) formations. The Khinantykul Formation, mostly comprising volcanic rocks, represents an upper part of the ophiolite association. The Kuyulpil Formation of more variable rock facies includes shallow-water clastic carbonates in northern sections and deep-water siliceous black shales in the southern sections. The Olenii Formation is flyschoid and sandy–shaly in composition with conglomerate horizons in its lower part. The underlying Ordovician deposits are found to be eroded at the base of the formation, although the main part of its clastic material is allochthonous. The Olenii Formation reflects a period of accretion or amalgamation of the Ordovician plate to the North American continent. The continent supplied much of the coarse clastic material derived from volcanites of the differentiated series and from the Cambrian organogenic limestones. This work is supplemented with complete lists of conodonts and radiolarians of the Elgeminai Group.

Key words: *Koryak Highland, Ordovician, terrane, conodonts, radiolarians, tektites.*

INTRODUCTION

The Ganychalan Terrane is observed on the left bank of the Penzhina River from the northeastern coast of Penzhina Bay to the upper reaches of the Main River (Fig. 1). The main part of the terrane is covered with Upper Cretaceous–Quaternary deposits.

The Ganychalan Terrane belongs to a category of complex or composite terranes (Coney *et al.*, 1980), has the folded–nappe structure, and comprises deposits accumulated in different geodynamic environments (Fig. 2).

Volcano-sedimentary deposits of the Ilpenei Formation, which are metamorphosed to the green-schist and glaucophane facies, occupy the lower structural position (Dobretsov, 1974; Ponomareva *et al.*, 1966). The metamorphic event is dated as 327 Ma old (Vinogradov *et al.*, 1994). Tectonic sheets of the Lower Paleozoic disintegrated ophiolites occur above these deposits (Markov *et al.*, 1982; Khanchuk *et al.*, 1992). The ophiolite sequence begins with a serpentinite melange sheet enclosing blocks of ophiolite and underlying rocks of the Ilpenei Formation. The Khinantynup sheet of peridotites, gabbroids, diabases, amphibolites, and mylonites is above the melange. The upper part of the ophiolite association consists of volcano-sedimentary deposits, which are basal in the Elgeminai Group (the Middle Ordovician–Lower Silurian). All the mentioned sheets are folded as a composite antiform overturned southeastward and are overlain with unconformity by the Aptian–Albian deposits of the Kedrovaya Formation.

In the southeast, the Ganychalan Terrane is thrust along the fault system over the Upupkin Terrane, which is composed of Cretaceous sequences and associated Devonian, Permian, and Triassic deposits. The Ganychalan Terrane is bounded on the northwest along the steep fault by the thick terrigenous Kharitonya Formation, which is assigned to the Tournaisian–Visean on the basis of abundant flora and fauna. The idea to distinguish these rocks as the separate Kharitonya Terrane (Khanchuk *et al.*, 1992) is still open to discussion, since in the Palmatkina block they occur unconformably over the Ordovician deposits (Migovich, 1963; Markov *et al.*, 1982).

The region discussed in this work is the only one within the Koryak–Kamchatka folded area where the Ordovician age of deposits is substantiated by fauna. Hence, it follows that the study of them is important, and the interregional correlations are necessary for reconstructing the Early Paleozoic geography and tectonics.

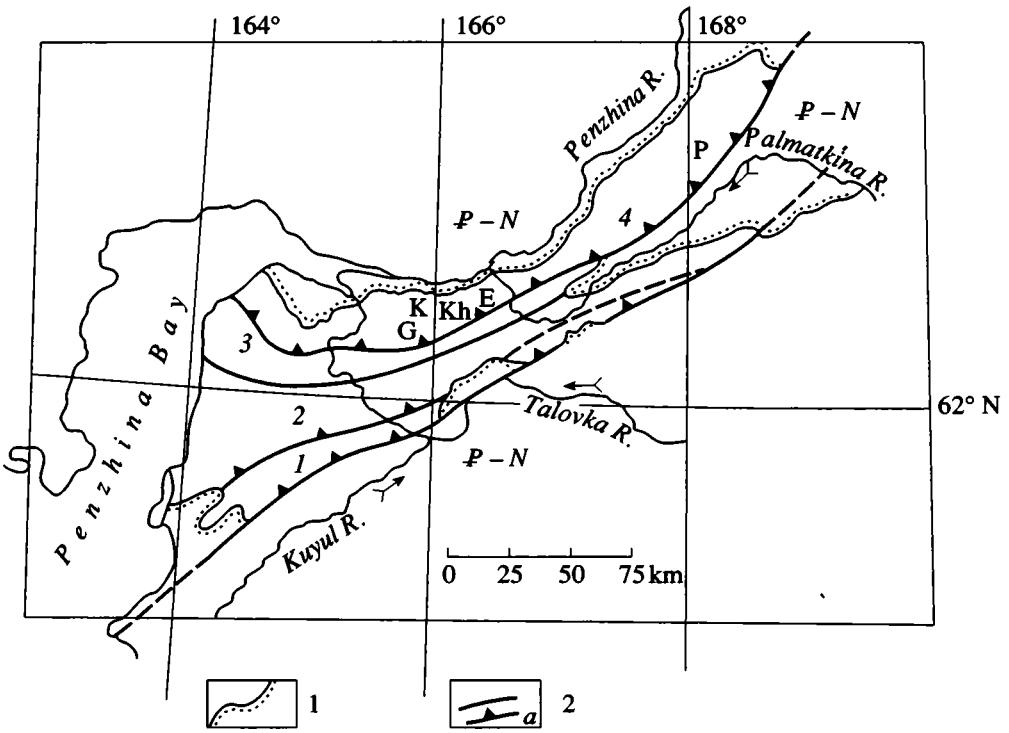

Fig. 1. Localities of type sections of the Ordovician deposits in the Penzhinskii Range: (1) basal horizons of the orogenic complex (P–N); (2) faults, including overthrusts; (2*a*) Indicated terranes: (*1*) Kuyul; (*2*) Ainyn; (*3*) Upupkin; (*4*) Ganychalan. Reference sections: (P) Palmatkina; (E) Elgeminai; (KH) Kharitonya; (K) Kuyulpil; (G) Ganychalan.

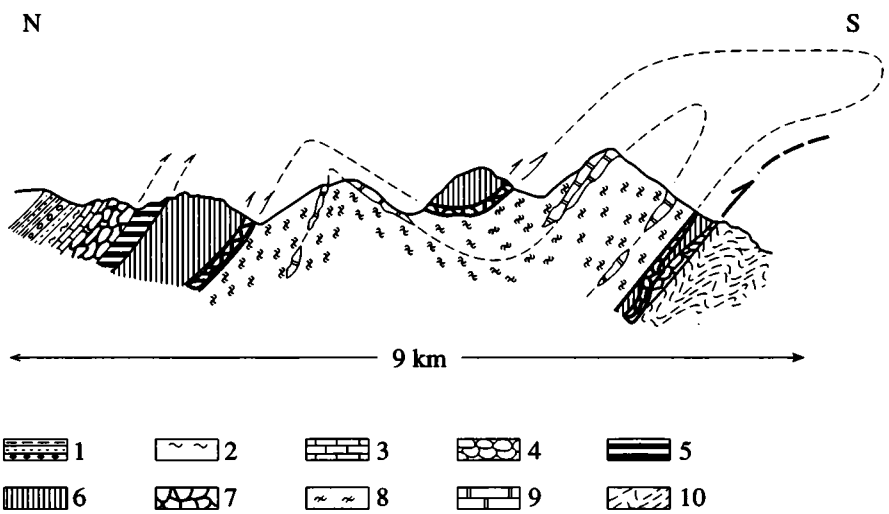

Fig. 2. Cross section of the Ganychalan Terrane: (1–4) Elgeminai sheet: (1) clastic rocks, (2) cherts, (3) limestones, (4) pillow lava; (5, 6) Khinantykul sheet: (5) sheeted dikes, (6) gabbro with later ultramafic intrusions; (7) serpentinite melange sheet; (8, 9) Ilpenei sheet: (8) green and blue shists, (9) marbles; (10) terrigenous rocks (P, T, K_1) of the Upupkin terrane.

INVESTIGATION HISTORY OF THE ORDOVICIAN DEPOSITS IN THE PENZHINSKII RANGE

The largest exposure of the Ordovician deposits referred to the Ganychalan Terrane is located in the Pontoneiskie Mountains of the Penzhinskii Range (Fig. 1). Most researchers assigned these deposits, along with other Paleozoic sequences, to the Ganychalan block on their tectonic schemes. During the medium-scale mapping carried out in this region during the 1940s–1950s, the Ordovician deposits were erroneously distinguished as a part of the Devonian sequence (Mikhailov, 1957). The second major exposure of Paleozoic rocks is located

in the Slautnye Mountains (the Palmatkina anticlinorium), 100 km northeast of the Ganychalan block. Migovich (1963) was the first to reveal the Ordovician–Silurian deposits within the limits of Penzhinskii Range precisely in this area. Zaborovskaya and Nekrasov (1974) later found these deposits in the Ganychalan block.

In succeeding years, only a few works on these rocks were published. Some detailed materials on the issue were represented in the work of Belyi *et al.* (1984), a book which remains little-known. These researchers suggested that the Ordovician deposits of Penzhinskii Range be distinguished as the Elgeminai Group, and their idea was used later during the large-scale mapping of the Talovka sheets.

In 1983–1984, when mapping (at a scale of 1 : 50 000) the area, which covered the most part of the Ganychalan block, geologists of the North Kamchatka Complex Geological Expedition (Bazhenov, Evglevskii, Semenov, and others) substantiated the subdivision of the Elgeminai Group into three units different in composition and age and also separated by unconformities. Afterward, when compiling the reference legend of the Talovka sheets, Sheludchenko and Evglevskii suggested that these sequences be distinguished as the Khinantykul (substantially volcanogenic; O_2k), Kuyulpil (diverse in composition and facies; O_2k–O_3k–as), and Olenii (sandy–shaly; O_3as) formations. The discussions below show that the paleontological material obtained allows a more precise age determination of the formations.

When substantiating the age of the formations, the authors of the legend also considered, in addition to the known findings of macrofauna (brachiopods, trilobites, ostracodes, crinoids, graptolites) and conodonts, new and as yet unpublished data on radiolarians, whose remains were found mainly in siliceous rocks of the Kuyulpil Formation. Nazarov, who was engaged in studying the radiolarians, passed to us, a short time prior to his death, these results in the form of an unfinished paper written together with Evglevskii and Semenov, as well as his conclusions on some samples.

We found it necessary to introduce in this work some of his materials concerning the Elgeminai Group, as he was a prominent expert in the Paleozoic radiolarian assemblages. We used data on the samples for which the final conclusion on the age had been made and the sampling localities had been pointed out.

DESCRIPTION OF SECTIONS

The Elgeminai Group is characterized in papers by Belyi *et al.* (1981, 1984) on the basis of three sections. Two of them (the Kharitonya and Elgeminai) are located within the Ganychalan block: one in the basin of the upper and middle courses of the Kharitonya River (the left tributary of the Penzhina River), the other on the left bank of the Malyi Upupkin River upper reaches (the left tributary of the Belaya River), southwest of the Mt. Elgeminai. The third section is in the Palmatkina anticlinorium. Of these three sections, we obtained new data only from the Kharitonya section.

In addition to three type sections, two sections important for characterizing the Elgeminai Group and its facial changes are exposed in more southern areas of the Ganychalan block and in upper reaches of the Kuyulpil and Ganychalan rivers (right tributaries of the Talovka River). They were not considered in the published works. Figure 3 demonstrates the structure and stratigraphic subdivision of the type sections of the Elgeminai Group discussed in this work.

The Elgeminai Section

The section of the Ordovician deposits exposed southwest of the Mt. Elgeminai summit is taken as the stratotype of the Elgeminai Group (Fig. 1). The deposits are folded into steep linear folds up to 1.5 km wide (Belyi *et al.*, 1984). The core of one anticline is composed of volcanic rocks of the lower part of the group exposed near the summit, whereas higher horizons are exposed on the anticline flanks and within the conjugated syncline displaced along the fault. The section comprises deposits of all three formations distinguished in the Ordovician.

The Khinantykul Formation mainly consists of massive amygdaloidal basalts and lenticular bodies of hyaloclastites. The upper 30–40 m of the formation are represented by a close alternation of lava flows, slaggy in places, hyaloclastites and lenses of pink to cream-colored and gray limestones up to 0.5 m thick. The exposed thickness of the Khinantykul Formation in the Elgeminai section does not exceed 350 m.

The Kuyulpil Formation, according to geological survey data, overlies with angular unconformity basaltoids of the Khinantykul Formation. The formaion in question mainly consists of light gray organic limestones with interlayers of dark gray and black cherts in the basal and top portions. The summit of Mt. Elgeminai is made up of limestones as well. The thickness of the formation varies from several meters to 80 m, which is probably due to erosion of its upper part. The Kuyulpil Formation yielded diverse macroflora and microfauna, which allows us to correlate the Ordovician deposits of the Palmatkina anticlinorium and the Ganychalan block.

In samples collected by Krasnyi within the southeastern flank of the Elgeminai anticline, Gagiev (1984) identified the following conodonts: *Falodus prodentatus* (Graves et Ellison), *Periodon aculeatus* Hadding, *Oistodus abudans* (Branson et Mehl), *O.* sp., *Belodina* cf. *compressa* (Branson et Mehl), *Dichognathus*? cf. *decipiena* Branson et Mehl, *Belodella*? aff. *ordovicica* Moskalenko, *Panderodus gracilis* (Branson et Mehl), *Ligonodina* sp., *Prioniodina* sp., *Ozarkodina* sp., *Scandodus* sp., and *Drepanodus* sp.

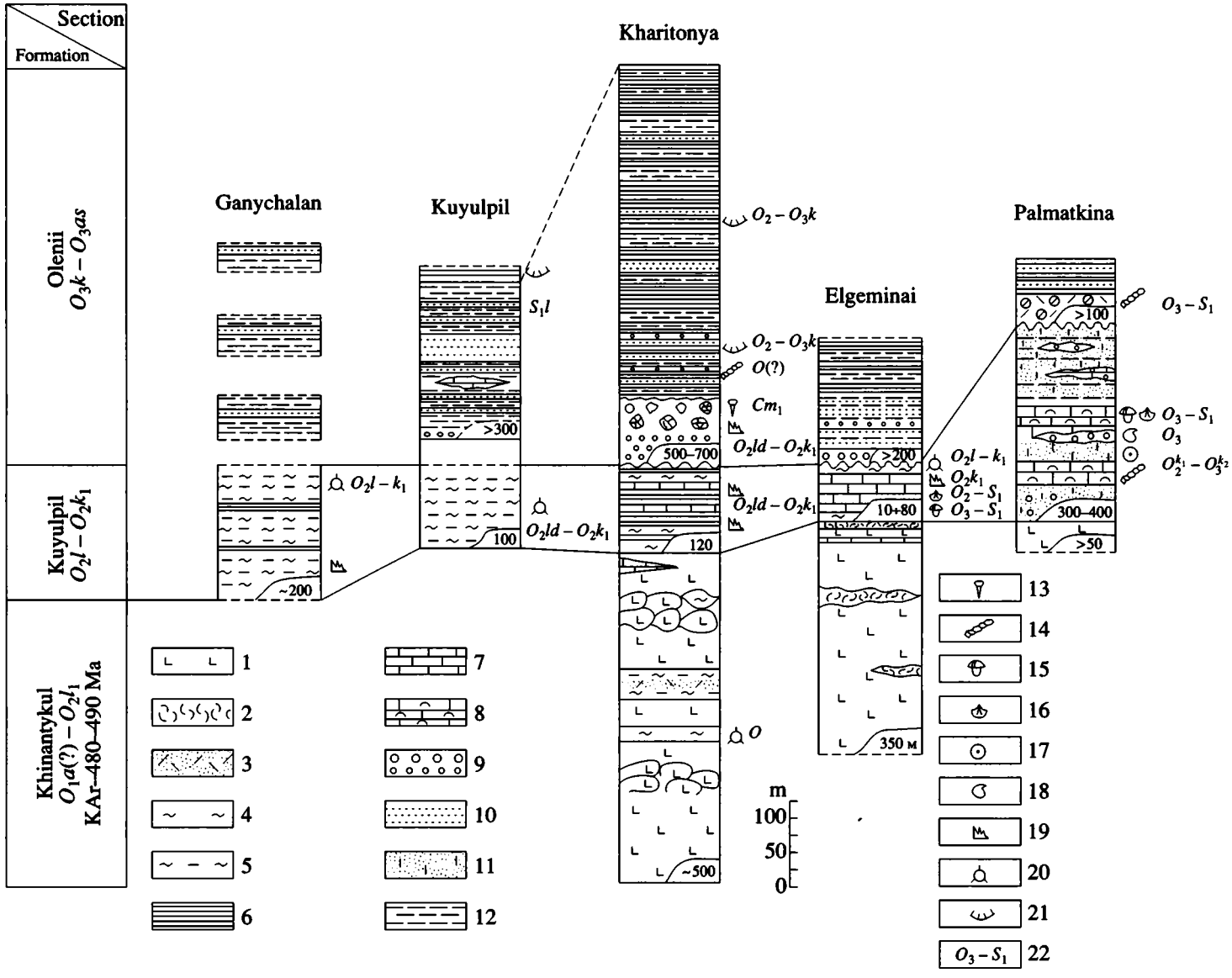

Fig. 3. Stratigraphic type sections of the Elgeminai Group: (1–12) rocks: (1) basalts, (2) hyaloclastites, (3) tuffs, (4) cherts, (5) siliceous shales, (6) mudstones, (7) limestones, (8) organogenic limestones, (9) conglomerates, (10) sandstones, (11) calcareous sandstones, (12) silty pelites; (13–21) fossils: (13) archaeocyathids, (14) corals, (15) trilobites, (16) brachiopods, (17) crinoids, (18) ostracodes, (19) conodonts, (20) radiolarians, (21) graptolites; (22) stratigraphic age of fossil groups.

The first and second taxons of the assemblage belong to the multiform species *Periodon aculeatus* Hadding, whose appearance in the evolutionary lineage of the *Periodon* genus is recorded in the Llanvirnian. It is Gagiev's opinion that, in general, this conodont assemblage indicates the early Caradocian age of the enclosing rocks.

Brachiopods similar in Oradovskaya's view to the Middle Ordovician–Early Silurian forms were collected from the same flank of the anticline. The Late Ordovician–Early Silurian (in Chugaeva's opinion) trilobites were found in limestones exposed on the opposite flank of the Elgeminai anticline (Belyi *et al.*, 1984).

Nazarov, when studying thin-sections of cherts from the Elgeminai section, revealed radiolarians *Inanihella* aff. *bakanasensis* Nazarov, *Ulcundia* cf. *incomperta* Nazarov, and *Proventocytum* sp., which characterize the age of the enclosing rock as ranging from the Arenigian–Llanvirnian to the early Caradocian.

The Olenii Formation, as in all sections of the Elgeminai Group, consists of substantially terrigenous rocks. Its lower part is composed of alternating lenses and beds of polymictic conglomerates, calcareous sandstones, and shaly siltstones. The thickness of the conglomerates ranges from 3 to 15 m. The amount and thickness of conglomerates increase in areas of the maximum erosion of limestones of the Kuyulpil Formation (Belyi *et al.*, 1984). Greenish gray shales and siltstones dominate in the upper half of the sequence. Its total visible thickness exceeds 200 m. No fossils have been found in the sequence. The assignment of this unit to the Olenii Formation is based on its occurrence above the Kuyulpil Formation and on the similarity of these sediments to deposits of the Olenii Formation of the Kharitonya section.

The total thicknes of the Elgeminai Group in the discussed section exceeds 700 m.

The Palmatkina Section

This section of the Elgeminai Group is important for revealing the facial changes in the Ordovician deposits of Penzhinskii Range. At the same time, its correlation with the Ganychalan section is complicated by a substantial facies diversity between them, as well as by abrupt changes in the composition of oryctocenoses, first of all by the disappearance of conodonts and graptolites. The Palmatkina anticlinorium is severely faulted, and exposures of different parts of the Elgeminai Group are spaced apart. Belyi *et al.* (1984) have compiled a composite section of the group and correlated it with the Elgeminai section.

Greenish gray massive basalts and their tuffs, whose apparent thickness is more than 50 m, occur at the base of the Palmatkina section. This unit should most likely be referred to the Khinantykul Formation.

The overlying sequence correlative with the Kuyulpil limestones of the previous section is of great interest. The sequence is composed of conglomerates, calcareous sandstones, and siltstones. The conglomerates comprise lenses and interlayers of gray marbleized limestones with abundant macrofossils. The limestones are of the reef type (Belyi *et al.*, 1984). The sequence is 150–180 m thick.

Trilobites found in the limestones are more diverse than those from the Elgeminai section, but they also remained unidentified at the species rank. In Chugaeva's opinion, the range of the trilobites is the Late Ordovician–Early Silurian.

The limestones also yielded a rich brachiopod assemblage of *Parastrophinella* sp., *Triplesia* sp. indet., *Strophenomena* sp. indet., *Sowerbyella* ex gr. *sladensis* Jones, *Dolerothis* cf. *intermedius* Nirif., *Tscherskidium* cf. *unicum* A. Nik., Atrypidae (*Pactatrypella kolymica* Orad. gen. et sp. nov.), *Cryptothyrella* (?) sp., and *Sowerbyella* sp. indet. The assemblage indicates that the enclosing rocks are the Late Ordovician–Early Silurian in age (determinations by Oradovskaya).

Diverse ostracod and crinoid assemblages unknown in the Ganychalan block are described from this section as well. Among ostracods, L.S. Til'man quoted forms typical of the Late Ordovician: *Winchellatia*? sp., *Steusloffina cuneata* (Steusloff), *S.* sp., *Oepikella*? *frequens* (Steusloff), *Brevidorsa* cf. *brevidorsata* Neekaja, and *B.* cf. *sarvi* Neekaja.

The crinoid assemblage is represented by *Squameocrinus* sp., *Apertocrinus* sp., *Fascicrinus* sp., *Multifidocrinus multifidus* (Jelt.), and *Sidencrinus* sp. In Stukalina's opinion, the age of the assemblage dates the enclosing rocks in the interval from the end of the Middle Ordovician to the beginning of the Late Ordovician (Caradocian). Among corals revealed from this section, Kachanov identified *Streptelasma* ex gr. *cyrtum* Neuman and *Palaeophyllum thomi* (Hall). Conodonts are represented by rare findings of *Trichonodella* sp.

As a whole, the fauna does not disprove its Caradocian age. Belyi and his coauthors correlated this sequence with the lower Caradocian limestones of the Elgeminai section based on the assumption of paleontologists on a similar type of trilobites and brachiopods from both sections.

A sequence of dark gray calcareous siltstones and fine-grained sandstones alternating with lenses of limestones and small-pebbled conglomerates with a calcareous matrix is referred by convention to the upper part of the Kuyulpil Formation of the Palmatkina section. The sequence is 150–200 m thick; the total thickness of the formation is 300–400 m.

Conventionally assigned to *the Olenii Formation* is a sequence with basal medium- to coarse-grained and poorly graded conglomerates cemented by a calcareous sandy matrix. Poorly rounded pebbles of the rocks are composed of limestones bearing brachiopods *Hesperorthis* sp. indet. and crinoids *Squameocrinus squamosus* (Jelt). The composition of pebbles and enclosed fauna undoubtedly indicate that the conglomerates

originated due to erosion of the underlying part of the section. Their matrix in places comprises colonies of the Late Ordovician–Early Silurian tabulates *Catenipora* sp. (identified by Kovalevskii). The thickness of the conglomerates is 40 m; they are replaced upsection by a sequence of gray and greenish gray phyllite-like shales intercalated with dark gray sandstones. The apparent thickness of the sequence is more than 50 m.

The total thickness of the Elgeminai Group of the Palmatkina anticlinorium averages 450–550 m.

The Kharitonya Section

The Kharitonya area of the Ganychalan block has been studied in detail and includes stratotypes of all the three formations of the Elgeminai Group, which comprise fossils.

The Khinantykul Formation is mainly composed of albitized basalts and spilites. Flows of amygdaloidal brecciated pillow basalts displaying hematitization, as well as flows of highly vesicular basalts grading into scoriaceous lavas, are associated in this unit with massive, often ophitic basalts.

According to our results, volcanic rocks of the Khinantykul Formation are similar in geochemistry to recent basalts of the oceanic spreading zones. In particular, they have rare-earth element spectra that are depleted in light lanthanides.

Rare lenses and interlayers (up to 1.5 m thick) of red jaspers and cream-colored limestones are observed among lava flows. Besides, the middle part of the sequence comprises several members (tens of meters thick) made up of tuffaceous–siliceous and siliceous siltstones, andesitic tuffs, jaspers, and jasperiod quartzites. The rock color varies from gray to greenish gray and reddish brown.

Nazarov has found remains of problematic microorganisms *Ulcundia*? sp. of Ordovician appearance in the sample selected from a layer of gray and violet jasper 6 m thick located 200–250 m below the formation top between spilites and tuffs. Since the ulcundians have been found along with Ordovician radiolarians in many samples from the overlying Kuyulpil Formation, their occurrence among the Khinantykul Formation may serve as an argument in favor of the assignment of the Khinantykul Formation to the Ordovician.

Data on the absolute age may be another factor in support of this. The K–Ar analysis of two bulk-rock samples of basalt selected by Yu.F. Naidenkov in the Kharitonya area yielded values of 480 and 490 Ma (Arenigian–Llanvirnian).

The Khinantykul Formation is closely associated with the underlying ophiolite section of the Khinantynup sheet, which is 500–1000 m thick. The section is described in works by Markov *et al.* (1982) and Khanchuk *et al.* (1992). The geochemical comparison of basalts with altered rocks of the diabase complex lying directly below them showed that, according to differentiation trends, the diabase dikes could not serve as feeders for extrusive rocks. At the same time, it is evident that volcanism of the Khinantykul Formation is related in origin to a deeper diabase complex of the ophiolite section.

It should be noted that, at present, there are no geochemical data that could allow a comparison between volcanites of the Elgeminai, Palmatkina, and Kharitonya sections.

The Kuyulpil Formation is represented by a sequence occurring with an erosional hiatus on the Khinantykul volcanites and comprising dark-colored members 10–50 m thick and separate layers of white and light gray limestones 5–6 m thick. The dark-colored members are made up of alternating banded dark and dark gray siliceous siltstones and phthanites with rare and thin (up to 1 m) interlayers of shales and black calcareous sandstones.

Gagiev (1984) has identified in limestone samples the following conodonts: *Periodon aculeatus* Hadding, *Prioniodina macrodentata* (Graves et Ellison), *Ligonodina tortilis* Sweet et Bergstrom, *Falodus predentatus* (Graves et Ellison), *Falodus* sp. A, *Loxognathus* cf. *grandis* Ethington, *Periodon* sp. indet., *Oistodus venustus* Stauffer, *Panderodus gracilis* (Branson et Mehl), *Microcoelodus* sp., *Scandodus* sp., *Drepanodus* sp., *Prioniodina* sp., and *Phragmodus* sp. The first four forms belong to the multielement species *Periodon aculeatus* Hadding, whose range is the Llanvirnian–early Caradocian. It is important for the dating that these four forms are associated in the Kharitonya section with representatives of another multielement species, *Periodon grandis* (Ethington), characteristic of the Caradocian–Ashgillian and terminating the phylomorphogenetic evolution of this genus. These are formal species *Falodus* sp. A and *Loxognathus* cf. *grandis* Ethington.

Based on the fact that the multielement species *Periodon aculeatus* Hadding is represented in the Kharitonya section (e.g., in the Elgeminai) locality by more recent formal species and also on the presence of the species *Periodon grandis* (Ethington), the enclosing limestones in both sections were dated back to the early Caradocian (Gagiev, 1984). In Gagiev's opinion, the deposits correspond to the upper part of the *Nemagraptus gracilis* Zone in the Llandeilian and Caradocian stratotype sections of Great Britain.

Conodonts *Periodon* cf. *aculeatus* Hadding, *Phragmodus* sp., and *Protopanderodus* sp. (identified by S.V. Dubinina) were extracted from two phthanite samples collected by Sokolov between limestone members. The first two forms are similar to those found in limestones, and their position is consistent with the abovecited inferrence on the age of the formation. Moreover, these data on the identical age of the limestones and enclosing cherts discredit the interpretation of Chekhov (1982), who considered this unit as an Early Cretaceous olistostrome with olistoliths of Ordovician limestones.

The total thickness of the Kuyulpil Formation averages 120 m.

The Olenii Formation rests on the underlying rocks with the erosional hiatus. A horizon of gravelstone and pebbly conglomerate 20 m thick and mainly consisting of fragments of siliceous rocks is observed at the base of the formation (Belyi *et al.*, 1984). It is likely to be a basal conglomerate, which is composed of products of the erosion of the bed. The pebbly conglomerate is replaced upsection by a thicker (about 100 m) horizon of unsorted boulder–pebbly polymictic conglomerate with a calcareous–sandy matrix. Well-rounded, oval, and flat pebbles prevail in this horizon. Pebbles of gray, massive, organic, and platy limestones and siliceous rocks are most abundant here. Fragments of siltstones, calcareous sandstones, and shales are less frequent. About 10% is represented by pebbles of igneous rocks, among which the high-alumina basaltic andesites, basalts, and diabases with a high content of alkalies and a low content of titanium dominate. In addition to them, pebbles of potassic alkali basalts, leucocratic gabbrodiorites altered to different degrees, and andesitic tuffs are present as well (Belyi *et al.*, 1984). Nekrasov (1976) also reported on solitary pebbles of felsite–porphyries and albite–epidote–chlorite shales. Chrome-spinelides are encountered in the conglomerate matrix.

Some pebbles of the igneous rocks are likely derived by erosion from the ophiolites and rocks of the Khinantykul Formation. In our opinion, the idea of Belyi *et al.* (1984) on the similarity of pebbles of high alumina and alkaline rocks with volcanites of the Bulkut Formation (the Caradocian) from the Cherskii Ridge has not been adequately substantiated in terms of age and geochemistry. It is most likely that they are products of erosion of an island-arc complex, whose source, like the source of the calcareous pebbles, is unknown among the surrounding structures of Mesozoides.

Naidenkov and, more recently, Sverbilova (PGA "Aerogeologia") collected fragments of the Lower Cambrian limestones with archaeocyathids in this horizon. Zhuravlev, who studied samples from Sverbilova's collection, detected in them such forms as *Cordilleracyathus* sp., *Graphoscyphia* sp., and *Ephia* sp. Present along with them are carbonate problematics *Tubulaconus kordeae* Handf. All the forms are characteristic of the lower part of the *Bonia–Olenellus* Zone distinguished in western North America and referred to the mid-Botomian. They are unknown from the Lower Cambrian deposits of the Siberian platform and Kolyma uplift (Zhuravlev, 1988). Calcareous algae characteristic of the Early Cambrian (*Renalcis granosus* Vologd., *Gordonophyton parvulum* Voron. et Drosd., *Kordephyton crinitum* (Kosde), and *Girvanella sibirica* Masl.) have been found in pebbles along with archaeocyathids and problematics. In Golozubov's collection (Khanchuk *et al.*, 1992), pebbles of Ordovician limestones and phthanites were encountered in addition to pebbles of the Lower Cambrian algal limestones, from which Popov identified *Renalcis pectunculus* Korde, *Girvanella problematica* Nich. et Ether., *Epiphyton* cf. *fruticosim* Vologd., and *Proaulopora* sp. Bondarenko extracted from limestones and identified conodonts of the *Pygodus anserinus* Zone of North America characteristic of the *Nemagraptus gracilis* Zone enclosing *Pygodus anserinus* Lamont et Lindstrum, *Cahabagnathus sweet* Bergstrom, *Protopanderodus vericostatus* (Sweet and Bergstrom), *Phragmodus* sp., *Periodon aculeatus* Hadding, and *Paltodus semisymmetricus* (Hamar). Rudenko extracted remains of the *Ulcundia* forms from phthanites.

Zhuravlev identified fragments of the Sphinctozoa sponges (*Amblysiphonella*), presumably from the conglomerate matrix. The presence of these sponges is a characteristic feature of the Cambrian–Devonian deposits in the eastern part of the Pacific ring belt (eastern Australia, California, Yukon, Alaska).

A member of similar thickness of fine-grained rocks with individual beds of small-pebbled conglomerates occurs above the described horizon. The clastic material of conglomerates is represented by siltstones, limestones, and siliceous and volcanic rocks, as well as by quartz and plagioclase (Nekrasov, 1976). Among these rocks, there are fragments of limestones with colonial corals, which are similar in structure, as Bondarenko and Sharkova concluded, to those encountered in both the Ordovician and Devonian rocks.

The main part of the member is composed of gray phyllitized siltstones and shales with closely spaced interlayers of small- and medium-grained calcareous polymictic sandstones up to 20 cm thick. Zaborovskaya and Nekrasov (1974) collected graptolites precisely from these shales, and this, in Koren's opinion, allows these beds to be dated back to the Middle Ordovician–Early Silurian time and thus proves for the first time the presence of Ordovician–Silurian deposits in the Ganychalan block. The subsequent and more complete sampling of fossils resulted in identification of the following graptolite species: *Dicellograptus* cf. *gurley* Lapw., *Climacograptus parrus* J. Hall., *C.* ex gr. *bicornis* (J. Hall.), and *Orthograptus* ex gr. *calcaratus* (Lapw.). Sobolevskaya and Koren' consider them as typical Caradocian forms (Belyi *et al.*, 1984). Thus, the erosion event at the base of the Olenii Formation in the Kharitonya section most likely occurred in the Caradocian at the boundary between the Middle and Upper Ordovician deposits.

The upper half of the Olenii Formation differs from the underlying member in the absence of conglomerate beds. Siltstone and shale members, which comprise interlayers of calcareous sandstones less than 3 m thick, dominate in it as well. The members are separated by several thicker (up to 30 m) horizons of massive, dense, greenish gray, small- and medium-grained sandstones, with foliated jointing in places. Quartz, plagioclases, carbonates, siliceous rocks, and more rarely, effusives prevail in their clastic fractions. Chromite is dominant

in the heavy fraction (50–90%). It is similar in chemical composition to chromite from ultramafic rocks of the Khinantynup sheet of the Ganychalan Terrane (data of Taskaev obtained with the microprobe UKHA-5P).

Graptolites *Dicellograptus* cf. *moffataensis* (Carr.), *Climacograptus* sp., *Ortograptus* ex gr. *amplexicaulis* (J. Hall.), and *O.* ex gr. *calcaratus* (Lapw.), which are characteristic, in Sobolevskaya and Koren's opinion, of the Late Ordovician (the *Orthograptus quadrimucronatus* Zone and probably the lower parts of the *Climacograptus longispinus supernis* Zone), were found in the middle part of the siltstone–shale member, 100–150 m above the layers containing the previous graptolite assemblage.

Nazarov extracted the Late Ordovician (including probably the Early Silurian as well) radiolarians *Inanihella* sp., *Inanigutta* sp., *Haplentactinia* sp., (*H.* ex gr. *silurica* Nazarov et Ormiston), and *Oriundogutta* sp. from siliceous rocks located probably near the boundary with the overlying Upper Cretaceous deposits.

The visible thickness of the upper sequence ranges from 300 to 500 m. Thus, the total thickness of the Olenii Formation in the Kharitonya section measures 500–700 m, and its age corresponds to the late Caradocian–Ashgillian.

The Kuyulpil Section

The Ordovician deposits of this section are exposed along the left trubutaries in the upper reaches of the Kuyulpil River. Relationships between the volcanogenic Khinantykul and sedimentary Kuyulpil formations are not clear. About 100 m of the section are not exposed in the contact zone.

The Kuyulpil Formation is represented by a banded sequence (100 m) of siliceous siltstones and phthanites, which yielded a diverse radiolarian assemblage of the Llandeilian–early Caradocian age (identification by Nazarov): *Haplentactinia juncta* Nazarov, *H.* cf. *armillata* Nazarov, *H.* sp. (*H.* cf. *baltica* Nazarov), *Inanibigutta aksakensis* (Nazarov), *I.* ex gr. *aculeata* (Nazarov), *Anakrusa meryacantha* Nazarov, *Oriundogutta ramifican* (Nazarov), *Cessipylorum* sp., and *Inanigutta unica* (Nazarov).

The sequence resembles the section of the Kuyulpil Formation in the Kharitonya River basin but differs in the absence of limestones.

The Olenii Formation comprises the following units (from the base upward):

(1) The member of rhythmically alternating phylitized siltstones and fine- to medium-grained sandstones with rare lenses of pelitomorphic limestones. The apparent thickness is 120 m.

(2) Sandstone beds with rare interlayers (up to 1 cm) of siltstones. The thickness is 80 m.

(3) The member of fine-grained sandstones closely alternating with phylitized siltstones. The apparent thickness is 100 m.

(4) A poorly exposed sequence of phylitized shales. Nekrasov has found the Early Silurian graptolites *Monograptus* sp. (identified by Koren') in the uppermost part of the sequence.

The incomplete thickness of the Olenii Formation in the Kuyulpil section is more than 300 m. It is likely close to the thickness of the formation in the Kharitonya River basin.

The Ganychalan Section

In the upper reaches of the Ganychalan River (the right tributary of the Talovka River), the Ordovician–Lower Silurian (?) deposits are exposed in the basin of its right tributaries: Zagadka and Mrachnyi creeks, and others. The deposits form a large block in the Ganychalan serpentinitic melange.

The Kuyulpil Formation is exposed mainly in the interfluve area of Zagadka and Mrachnyi creeks.

Members of phthanites closely alternating with black shales dominate in the formation. The thickness of the members measures tens of meters. Phthanites are composed of a siliceous mass recrystallized to different degrees and, as a rule, bearing some radiolarian relicts.

Between the well-exposed phthanite members forming the prominent relief forms, there are poorly exposed members with terrigenous rock fragments scattered around and consisting mainly of mudstones, siltstones, and fine-grained calcareous sandstones locally displaying small tonguelike basal hieroglyphs, small ripple marks, and intersecting mud-eater tracks.

The total thickness of the Kuyulpil sequence can be evaluated only approximately because of limited exposures and folding. It seems to be 200 m on average.

In the lower part of the formation, we have found conodonts: *Periodon aculeatus zgierziensis* Dzik, *Paroistodus originalis* (Sergeeva), *Drepanodus arcuatus* Pander, and *"Acontiodus" arcuatus* Linds. (identified by Dubinina). The assemblage indicates the early Llanvirnian age of the enclosing rocks. Other samples from overlying rocks yielded no conodonts. A single sample from the uppermost part of the formation is the only exception. A conical element of Ordovician appearance was extracted from it.

Formerly, Nazarov extracted radiolarians *Inanibigutta* cf. *aksakensis* (Nazarov), *Inanigutta* sp., *Inanihella bakanasensis* (Nazarov), *Haplentactinia juncta* Nazarov, and *Ulcundia incomperta* Nazarov from phthanites of the Kuyulpil Formation. In his opinion, the assemblage indicates the Llanvirnian–early Caradocian age of the enclosing rocks. The samples were probably taken from the upper half of the formation, although their exact position in the section is unknown. In our collection of phthanites selected throughout the section, it was possible to extract radiolarians suitable

for further identification only from samples taken from the upper part of the formation (personal communication of V.S. Rudenko). The degree of preservation of radiolarians in the lower half of the formation is very poor.

It is interesting to note that tens of small (less than 0.1 mm) globules were encountered in one phthanite sample from the upper part of the formation in the insoluble residue after treatment of the rock by 5% hydrofluoric acid (the common method of extracting conodonts from cherts). The globules have a metallic luster but are not magnetic. At the same time, they easily stick to a needle point and even form columns of several pieces arranged one above the other. This can probably be explained by their electrostatic charge. Semiquantitative spectral analysis with the help of a laser microanalyzer (LM-1) yielded the following sequence of the relative content of elements: Ti, Ca > Al > Si > Mg. Their photographs in the Debai–Sherer chamber (CuK_α-emission) with different exposures gave no results in terms of their phase nature. Thus, it is hard to judge what these globules are composed of. Data on the homogeneity or zonation of the globules are lacking, and it is not clear how much they retained their original composition after treatment by hydrofluoric acid. Unfortunately, we have run out of rock material from this sample, which excludes the possibility of special studies that could help in tackling all these questions.

For the moment, we can point out that the globules more closely resemble tectites in form and size. It is well known that the presence of cosmic dust may reach a perceptible amount in modern condensed pelagic sediments, such as "abyssal red clays." Should this be the case, the globules indicate separate periods of very low sedimentation rates in the course of formaton of the phthanite sequence of the Ganychalan section. On the other hand, it is common knowledge that the amount of cosmic material falling upon the Earth's surface is controlled by planetary events and subject to variations. If additional actual material on the Ordovician deposits is obtained, the presence of tectites in rocks can be an ancillary reference point for their correlation.

The Olenii Formation is more widespead in the upper reaches of Ganychalan River, as compared to the Kuyulpil Formation. Structurally, the deposits of the formation are confined to the same sheet of the melange. They are composed of fine-grained calcareous sandstones and philitized silty pelites typical of the formation.

COMPARISON WITH THE ORDOVICIAN DEPOSITS OF THE VERKHOYANSK-KOLYMA REGION

The Ordovician deposits are widespread in northeastern Russia. They are known in the southeastern Siberian platform and Verkhoyansk–Kolyma folded region. The deposits have been heavily studied at present in terms of detecting their stratigraphic position by different fauna groups, as well as regarding their composition, facies, and peculiar features of sedimentation and volcanism. Paleogeographic aspects of the tectonic evolution of the region in the Ordovician were discussed by Bulgakova (1986, 1991). Various structural zones differ greatly in the completeness of sections, facies, and formation type of the Ordovician deposits. Without going into detail, it should be noted that carbonate and different clastic, often coarse, rocks, which accumulated in different areas of the paleoshelf, prevail throughout the Verkhoyansk–Kolyma folded region. Zones of predominant development of deep-water fine-clastic formations can also be recognized against the background of this prevalence.

It is believed that, after the existence of the Kolyma land in the Late Cambrian–early Tremadocian, the subsequent history of the Verkhoyansk–Kolyma folded region was related to the general transgression and formation of a spaceous shelf basin along the eastern Siberian platform. In addition to the general subsidence, an active destruction of the region took place and resulted in the development of deep troughs filled with deep-water clastic deposits derived from the slopes. The destruction was accompanied by trachybasaltic and basaltic andesite volcanism. The strike of the troughs in modern coordinates steeply cuts the sublatitudinal zonation of shelf deposits. Abrupt lithofacies transitions from shallow-water to deep-water deposits are very characteristic.

The correlation of the Elgeminai Group with the Ordovician deposits of the Verkhoyansk–Kolyma folded region revealed the data as follows below.

Shallow-water facies of the Kuyulpil Formation in the Palmatkina and Elgeminai sections are well compatible with the shelf-type deposits. At the same time, more pelagic deposits of the Kuyulpil Formation, which are exposed in the Kharitonya, Kuyulpil, and Ganychalan sections, differ greatly from the deep-water complexes of the Verkhoyansk–Kolyma region. The last deep-water complexes are of the clastic type with a large share of micritic carbonate material and, only in places, with a high silica content. Siliceous formations proper are absent throughout the Verkhoyansk–Kolyma region. On the contrary, the replacement of shallow-water carbonate–clastic deposits by the phthanite–black-shale formation is characteristic of the Middle Ordovician sections in the Penzhinskii Range. It is known that phthanite–black-shale formations are widespread among the Lower Paleozoic, in particular, Ordovician pelagic deposits of the Central Asian foldbelt and in the North America terranes.

In the Verkhoyansk–Kolyma region, the Middle–Upper Ordovician deposits continue up the upper Tremadocian and Arenigian sequences. The Lower Ordovician deposits have not yet been found in the Penzhinskii Range.

Manifestations of the alkaline basitic volcanism typical of the continental rift structures are revealed in

the Verkhoyansk–Kolyma sections. The volcanogenic complex of the Khinantykul Formation of the Penzhinskii Range represents the typical spilite–diabase complex characteristic of ophiolite associations of foldbelts.

Hence, there are fundamental differences between the Ordovician deposits of the Ganychalan Terrane and Ordovician deposits of the Verkhoyansk–Kolyma folded region.

In this regard, inferences of Zhuravlev based on the comparative study of archaeocyathids from the Lower Cambrian deposits of the Verkhnyaya Kolyma Uplift and from conglomerate pebbles of the Olenii Formation of the Kharitonya section are very important. Forms from the uplift are widespread in the Siberian platform and belong to the African–Siberian–Antarctic archaeocyathid province. Forms found in the Ordovician conglomerates along with carbonate problematics are typical of the Koryak–American province (Zhuravlev, 1988, 1992). Coexistence of the latter with the Ordovician Sphinctozoa remains typical of North America and absent in Siberia gives no way to relate the formation of these conglomerates to the erosion of any area of the Verkhoyansk–Kolyma foldbelt.

The original position of the Ganychalan Terrane remains unknown. It can be considered as a "suspect terrane" (Coney *et al.*, 1980). The type of volcanism, the presence of deep-water phthanites, and the fauna composition in the Ordovician deposits indicate an allochthonous, allogenic nature of the terrane and a complicated history of its formation. The time of its attachment to or, at least, its convergence with the continental margin is determined by the age of the Olenii Formation, the basal layers of which contain abundant clastics of differentiated volcanites and Cambrian organic limestones. The composition of the clastics prevents the Siberian and Verkhoyansk–Kolyma structures from being considered as its source. Thus, it may be inferred that, in the Ordovician, the Ganychalan Terrane was located near North America or was accreted to it. Afterward, the terrane was separated from this continent and displaced toward Asia. The Carboniferous and Permian flora and fauna of the Kharitonya and Upupkin terranes allow a suggestion that the Ganychalan Terrane was located at that time in the northern latitudes near the convergent boundary between Panthalassa and Asia. The time of the terrane accretion to Asia is determined by the Aptian–Albian age of the postaccretionary deposits of the Kedrovaya Formation (Khanchuk *et al.*, 1992).

CONCLUSION

The review of the material available and analysis of new data resulted in the following stratigrafic conclusions:

(1) The section of the Elgeminai Group spans the interval of the Middle and Upper Ordovician (Llanvirnian–Ashgillian). The presence of the Llanvirnian deposits was substantiated by fossils for the first time.

(2) In all sections, the group can be subdivided into three complexes: the lower (volcanogenic), middle (diverse in composition and changeable in facies), and upper (sandy–shaly, persistent in composition and structure), all corresponding to three formations suggested by Sheludchenko and Evglevskii in the local stratigraphic scale of the Ordovician deposits of the Penzhinskii Range.

(3) The (lower) Khinantykul Formation represents a typical volcanogenic complex of the ophiolite associaion. The association is most extensively exposed in the Kharitonya section, where volcanic rocks of the formation terminate the ophiolites of the Khinantykul sheet. The formation is dated back to the Llanvirnian (probably Arenigian–Llanvirnian).

(4) The (middle) Kuyulpil Formation is clearly confined (by conodonts in pelagic sections) to the interval from the Llanvirnian to the early Caradocian inclusive (the *Nemagraptus gracilis* Zone of the graptolite scale). Radiolarians found in these sections are also of the Llanvirnian–Caradocian age. Fossils of other faunal groups from shallow-water facies are not in conflict with this inference, although their age indicates a much larger interval of the stratigraphic scale. The shallow-water sediments give way to deep-water facies southwestward, i.e., from the Palmatkin to the Ganychalan block.

(5) The (upper) Olenii Formation corresponds by graptolites to the late Caradocian and Ashgillian (including the *Orthograptus quadrimucronatus* Zone and probably the lower parts of the *Climacograptus longispinus supernis* Zone). The radiolarian assemblage found in the upper part of the formation is well correlative with data on graptolites.

(6) Erosional hiatuses and local unconformities are revealed between the formations in the Penzhinskii Range. The largest unconformity and intense erosion of underlying rocks are noted at the base of the Olenii Formation, i.e., at the boundary between the Middle and Upper Ordovician. This level is suitable to be used as an additional reference point when correlating the deep-water (southern) and shallow-water (northern) sections of the Elgeminai Group.

(7) As a whole, the Ordovician deposits in the Ganychalan Terrane are similar to coeval North American deposits and differ greatly from those of the Verkhoyansk–Kolyma region. Special studies are necessary to understand which of the North American terranes is most similar to the Ganychalan Terrane.

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REFERENCES

Belyi, V.F., Kolyasnikov, Yu.A., and Krasnyi, L.L., Ordovician Deposits of the Koryak Highland, *Dokl. Akad. Nauk SSSR*, 1981, vol. 259, no. 6, pp. 1416–1419.

Belyi, V.F., Kolyasnikov, Yu.A., and Krasnyi, L.L., The Lower Paleozoic Stratigraphy of the Penzhinskii Range (Southwestern Part of the Koryak Highland), in *Paleontologiya i biostratigrafiya Koryakskogo nagor'ya* (Paleontology and Biostratigraphy of the Koryak Highland), Magadan: SVKNII DVNTs Akad. Nauk SSSR, 1984, pp. 19–36.

Bulgakova, M.D., *Litologiya ordovikskikh otlozhenii Severo-Vostoka SSSR* (Lithology of Ordovician Deposits in the Northeastern USSR), Moscow: Nauka, 1986.

Bulgakova, M.D., *Rannii-srednii paleozoi Severo-Vostoka SSSR* (The Early–Middle Paleozoic of the Northeastern USSR), Yakutsk: "Poligrafist," 1991.

Chekhov, A.D., Tectonics of the Talovka–Pekul'nei Zone, in *Ocherki tektoniki Koryakskogo nagor'ya* (Synopses of Tectonics of the Koryak Highland), Moscow: Nauka, 1982, pp. 70–106.

Coney, P.J., Jones, D.L., and Monger, J.W.H., Cordilleran Suspect Terranes, *Nature*, 1980, vol. 288, pp. 329–333.

Dobretsov, N.P., *Glaukofanslantsevye i eklogit-glaukofanslantsevye kompleksy SSSR* (Glaucophane-Schist and Eclogite–Glaucophane-Schist Complexes of the USSR), Novosibirsk: Nauka, 1974.

Gagiev, M.Kh., Ordovician Conodonts from the Pontoneiskie Mountains, in *Paleontologiya i biostratigrafiya Koryakskogo nagor'ya* (Paleontology and Biostratigraphy of the Koryak Highland), Magadan: SVKNII DVNTs Akad. Nauk SSSR, 1984, pp. 6–18.

Khanchuk, A.I., Golozubov, V.V., Panchenko, A.V., Ignat'ev, A.V., and Chudaev, O.V., Ganychalan Terrane of the Koryak Highland, *Tikhookean. Geol.*, 1992, no. 3, pp. 82–93.

Markov, M.S., Nekrasov, G.E., and Palandzhyan, A.S., Ophiolites and Melanocratic Basement of the Koryak Highland, in *Ocherki tektoniki Koryakskogo nagor'ya* (Synopses of Tectonics of the Koryak Highland), Moscow: Nauka, 1982, pp. 30–70.

Migovich, I.M., Paleozoic and Early–Middle Mesozoic Deposits of the Penzhinskii Range, in *Geologiya Koryakskogo nagor'ya* (Geology of the Koryak Highland), Moscow: Gosgortekhizdat, 1963, pp. 38–49.

Mikhailov, A.F., Paleozoic and Lower Mesozoic Deposits of the Penzhinskii Range, in *Tr. Mezhvedomstvennogo soveshchaniya po razrabotke unifitsirovannykh stratigraficheskikh skhem Severo-Vostoka SSSR, 1957* (Proc. Interdepartmental Conference on the Unified Stratigraphic Schemes of the Northeastern USSR), Magadan: SVKNII DVNTs Akad. Nauk SSSR, 1959, pp. 55–58.

Nekrasov, G.E., *Tektonika i magmatizm Taigonosa i severozapadnoi Kamchatki* (Tectonics and Magmatism of the Taigonos Peninsula and Northwestern Kamchatka), Moscow: Nauka, 1976.

Ponomareva, L.G. and Dobretsov, N.L., New Data on Paleozoic Stratigraphy of the Penzhinskii Range, *Geol. Geofiz.*, 1966, no. 4, pp. 90–98.

Vinogradov, V.I., Yurkova, R.M., Sokolov, S.D.,, *et al.*, Rb/Sr Isotopic Dating of Dynamometamorphic Rocks of the Penzhinskii Range, Kamchatka, *Geotektonika*, 1994, no. 5, pp. 63–69.

Zaborovskaya, N.B. and Nekrasov, G.E., Abstracts of Papers, *Mezhvedomstvennoe stratigraficheskoe soveshchanie po dokembriyu i paleozoyu Severo-Vostoka SSSR* (Interdepartmental Conference on Precambrian and Paleozoic of the Northeastern USSR), Magadan: SVKNII DVNTs Akad. Nauk SSSR, 1974, pp. 19–20.

Zhuravlev, A.Yu., Early Cambrian Archaeocyathids from the Extreme Northeast of the USSR, in *Kembrii Sibiri i Srednei Azii* (Cambrian of Siberia and Central Asia), Moscow: Nauka, 1988, pp. 97–110.

Zhuravlev, A.Yu., Was North America Ever a Chukotka Terrane? in *1992 ICAM Abstracts Anchorage, Alaska*, 1993, p. 66.

Stratigraphy and Geological Correlation, Vol. 5, No. 6, 1997, pp. 604–614. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 5, No. 6, 1997, pp. 85–95.
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Results of Paleomagnetic Studies of Pleistocene Moraines in the European Part of Russia

V. A. Bol'shakov

Moscow State University, Vorob'evy gory, Moscow, 119899 Russia

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Abstract—The results of paleomagnetic studies of moraine deposits are analyzed. The observation data imply that moraine beds display a considerable scatter of magnetization vectors regardless of the rock age. It is inferred that the anomalous magnetization vectors recorded in moraines might be caused not only by geomagnetic excursions, but also by the specific conditions of magnetization of the moraine beds. Opportune examples are given to show that the granulometric composition of the magnetic fraction in moraines can serve as one of the factors determining these conditions. Statistically justified reversed magnetizations were detected in the exposures of the Pleistocene moraines.

Key words: *moraine, paleomagnetism, stratigraphy, declination, inclination, close grouping of magnetization vectors.*

INTRODUCTION

Though the investigation of moraine deposits was started more than half a century ago, there are still a number of important problems that remain unsolved, such as the determination of the number of global Pleistocene glaciations, the boundaries of their areas, and their stratigraphic position. Magnetic and paleomagnetic methods were applied in this research, along with lithological methods, to characterize the moraine deposits. As noted earlier (Bol'shakov, 1984; 1989), the magnetic data can be used for local correlation and differentiation of moraine beds, but their stratigraphic allocation can be determined only by applying other data of paleogeographic analysis. The purpose of the paper is to give an analysis of paleomagnetic data obtained by many researchers on the East European moraines and to present the results of paleomagnetic studies of Pleistocene moraines in the European part of Russia. With this aim in view, the stratigraphic scheme of glacial deposits is employed, which was elaborated by Sudakova (1990), with whom we have collaborated since 1977. Another reason for using this scheme is that most of the paleomagnetic studies of moraines in the European part of the former Soviet Union were carried out on the basis of this stratigraphic scheme with units corresponding to the Okaian, Dnjeperian, Moskowian and Kalininan glaciations, though not without certain discrepancies. For example, I am not in agreement with Sudakova's conclusion (Sudakova, 1990) about the age of the upper part of the three-layered Likhvinian moraine (Bol'shakov, 1984), but rather with the conclusion in the later work *(Stratigrafiya ...*, 1992) on a different stratigraphic scheme of glacial deposits.

RESULTS

The first paleomagnetic and magnetic studies of moraines in the European part of the USSR were carried out by Goncharov (1965) and Trukhin (1969). The latter was the first to indicate the presence of the reversed component of magnetization in the moraine samples of the Dnjeperian Glaciation and to conclude that "the reversed component I_n is caused by the negative magnetostatic interaction," and that "the reversed component I_n is of the magnetic viscosity origin". Further research in other regions, however, resulted in a different interpretation of the obtained data, when they were attributed to a new event in the history of the geomagnetic field during the epoch of maximal glaciation (Kulikov *et al.*, 1973). This epoch was later called either the Odintsovo–Galich (Trukhin, 1977), or the Chagan (Faustov *et al.*, 1986), or the Chagan–Dnieper (Pospelova, 1989) event. However, as noted by Sudakova, "as yet there are no definite proofs that the Odintsovo–Galich and Chagan events were synchronous" (Sudakova, 1990, p. 56). The discovery of the Earth's magnetic field (EMF) anomaly of the Dnjeperian Glaciation epoch, and the possibility of its recording in the Dnjeperian moraine opened up the possibility to obtain an important stratigraphic and correlation marker distinguishing this moraine. Later, a number of publications presented information on the reversed magnetization of the Dnjeperian moraines (Desyatova *et al.*, 1973; Eremin *et al.*, 1973; Faustov *et al.*, 1974; Gaigalas and Pevzner, 1976; Isaeva *et al.*, 1978; Bol'shakov and Faustov, 1979; Faustov, 1981; Lazukov *et al.*, 1982). In almost all of these publications, the magnetization of the Moskowian and Kalininan moraines was treated as normal. Moreover, data were published on

the reversed magnetization of the Okaian moraine (Zubakov and Kochegura, 1973; Gaigalas and Pevzner, 1976; Sudakova and Bol'shakov, 1977; Isaeva *et al.*, 1978; Sudakova *et al.*, 1982) and the Don moraine (Kulikov and Krasnenkov, 1976; Semenov, 1994). Moreover, it should be emphasized that in the reversely magnetized moraines all the authors revealed a particularly wide scattering of magnetization vectors I_n and the almost invariable presence of normally or positively magnetized samples (with positive J inclination). Therefore, it seems obvious that in this case the term "reversely magnetized" is incorrect. It is more appropriate, apparently, to use the term "anomalously magnetized," as was also pointed out by Faustov (Faustov, 1981).

There are different explanations for the great scattering of I_n vectors in samples from the Dnjeperian moraine. It is supposed that the initial reversed magnetization is distorted either by the highly stable normal viscose magnetization (Trukhin, 1977), or by the secondary magnetization that appeared in the normal field during the freezing and thawing of meraine loams (Faustov *et al.*, 1974; Faustov, 1981). Ryabushkin and Pevzner (1978) suggested a model for the moraine samples, in which the systematic I_n component reflecting the EMF changes is associated with the clay–silt fraction of the moraines, whereas the random I_n component, independent of the EMF, is connected with the coarser gravel–pebble fraction. Consequently, if the random component of magnetization dominates, then the impact of I_n vectors on the hemisphere of reversed polarity can be caused merely by stochastic effects and, therefore, it is not associated with the presence of the reversed magnetization component. The practical recommendation for determination of the true vector of the ancient EMF is to study a greater number of samples. Incidentally, this publication (Ryabushkin and Pevzner, 1978) was actually the only one to set forth the statistical characteristics for the paleomagnetic study of moraines. However, neither in that paper, nor in any other publication listed herein (except those by Faustov and myself), the initial paleomagnetic data are presented in the form of stereograms of I_n vectors. Only their interpretation is published, and this, of course, hinders the analysis of the data.

At the same time, in my paper (Bol'shakov, 1982), I remarked on the absence of distinct criteria for differentiation of the Moskowian and Dnjeperian moraines by paleomagnetic data. There are papers casting doubt also on the existence of certain geomagnetic field excursions, and the more so on the possibility of distinguishing these excursions in moraine deposits (Verosub and Banerjee, 1977; Hus and Geeraerts, 1986). The latter contention is justified by the erratic effect of permafrost processes on the magnetization of loess beds in Belgium. There is a certain contradiction in the paleomagnetic data on moraines as well. For example, in some papers the magnetization of the Okaian and Dnjeperian moraines is treated either as normal, or as reversed (Zubakov and Kochegura, 1973; Gaigalas and Pevzner, 1976), while other authors insist on the reversed initial magnetization of moraines of this age (Isaeva *et al.*, 1978; Faustov *et al.*, 1986). There is a discrepancy in the data on the Dnjeperian (Eremin *et al.*, 1973) and Don moraines (Kulikov and Krasnenkov, 1976) in the basin of the Khoper River. As it is now acknowledged (*Stratigrafiya ...*, 1992), both moraines form a single moraine of the Don Glaciation. Nonetheless, in the first locality, the lower part of the moraine and the uppermost part of the submoraine clay member are reversely magnetized, while in the second area only the uppermost part of the moraine shows the reversed magnetization.

In total, the published data prompt the following conclusions:

1) The magnetization of the moraine deposits is oriented (Goncharov, 1965; Isaeva *et al.*, 1978).

2) The early and middle Pleistocene moraines in the European part of the Soviet Union have anomalous magnetization vectors correlative with a certain time period of reversed EMF, the record of which in moraines is distorted. The Moskowian and Kalininan (late Pleistocene) moraines are normally magnetized.

3) The paleomagnetic data on moraines are contradictory and even doubtful.

Since there are certain discrepancies in the actual paleomagnetic data on moraines and in their interpretations, the attitude of researchers to these results is, therefore, more or less critical.

Observation materials. My paleomagnetic studies covered the major moraines on the territories of the Kaluga, Moscow and Yaroslavl regions, and in Mordovia. The studied sections in the central part of the Russian plain show moraine beds corresponding to the Okaian, Dnjeperian, Moskowian and Kalininan glaciations (Sudakova, 1990). In addition to the Bryan'kovo and Tarusa sections on the Oka River (Sudakova and Bol'shakov, 1977; Sudakova *et al.*, 1982), I also studied the Okaian moraine in Moscow (the Ochakovka section). The results are shown in Fig. 1a. Figs. 1–4 demonstrate the I_n vectors measured after the thermal cleaning of rock samples in the nonmagnetic space at a temperature from 180 to 220°C during two to five hours. The cleaning almost always increased the I_n vector scattering and usually reduced by half clusters of the K collection. The most detailed studies of the deposits were carried out at the Satino Research Test Area (Kaluga region) of the Geographical Department of Moscow State University (Bol'shakov and Faustov, 1979). The studies showed that the Dnjeperian moraine has a much greater scatter of I_n vectors than the Moskowian moraine. The five studied exposures of the Dnjeperian moraine produced samples with the negative J and showed a wide scatter of declination and inclination angles. However, I have observed that certain sections of the Moskowian moraine yielded samples with negative inclinations. Figs. 1b and 1c show stereograms

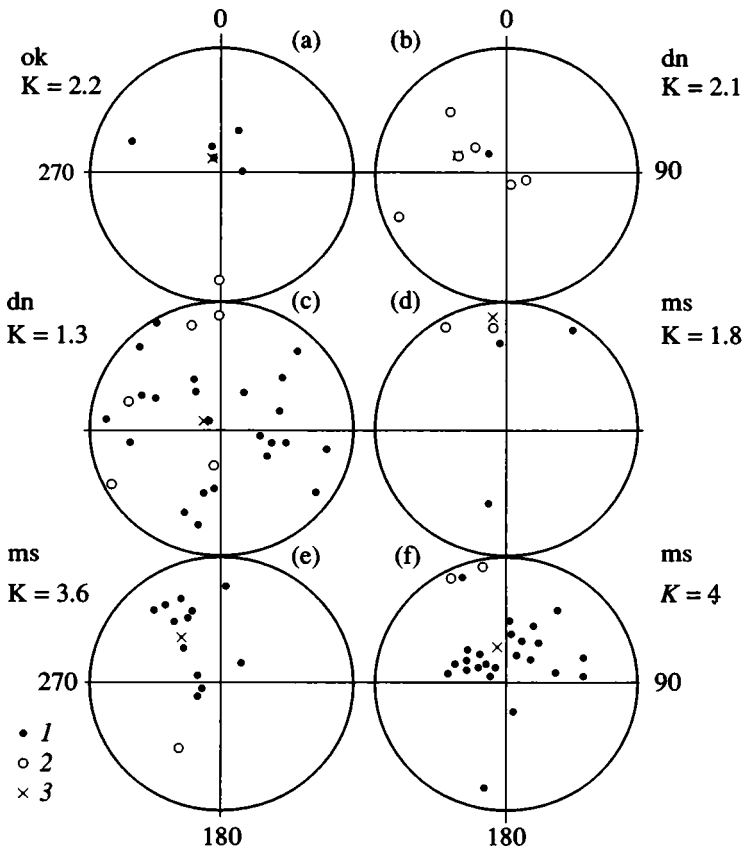

Fig. 1. Stereographic projections of magnetization vectors in moraine samples: (a) Ochakovo; (b, c) Satino, Volchenkovskii Gorge; (d, e) Satino, Sov'yaki and Sokolikha; (f) Mosal'sk–Zvenigorod–Moscow route. Symbols for Figs 1–4: (*1*) projections on the lower hemisphere; (*2*) projections on the upper hemisphere, (*3*) average direction of magnetization vectors for the sample collection; (K) clustering value; indices for moraines: (dns) Don, (ok) Okaian, (dn) Dnjeperian, (ms) Moskowian, (kl) Kalininan.

of I_n vectors in samples from the Dnjeperian moraine at the Volchenkovskii Gorge. The visible thickness of the moraine is about 7 m. The samples were collected on average with an interval of 0.5 m. Fig. 1b demonstrates data obtained from the interval of most intense negative magnetization (4–5 m from the top of the moraine). Fig. 1c shows data on the remaining section of the moraine. Figs. 1d and 1e represent data obtained from the samples of the Moskowian moraine recovered from the Sovyaki and Sokolikha sections in the Satino Test Area. Fig. 1f presents I_n vectors in samples of the Moskowian moraine selected from seven sections located along the Mosal'sk–Vereya–Zvenigorod–Moscow route.

The moraine of the Dnjeperian Glaciation in the Spas-Kamenskii section (Dmitrov region) was studied in detail. The color of the moraine beds of Moskowian and Kalininan(?) age are brown–buff and red–buff. The results are given in Figs. 2a and 2b (Fig. 2a represents data on the two overlying beds). An important site for this study was the Cheremoshnik section near Rostov Velikii (Figs. 2c–2g), where three moraine beds, including the debatable Kalininan Bed, were studied (*Putevoditel'* ..., 1969; Sudakova, 1990). It should be noted that the lower moraine beds of clearings 201 (Fig. 2f) and 205 (Fig. 2e) dated by the Dnjeperian Glaciation, differ by both appearance and magnetic properties. The moraines of Moskowian age in clearings 204 (Fig. 2d) and 202 (Fig. 2g) have similar differences. The study of the nearby Shurskol section revealed the reddish–brown Moskowian moraine and the brownish–gray Dnjeperian moraine (Fig. 2h, 2i).

The next series of sections was studied along the Yaroslavl–Rybinsk route. In the section near the Pechegda River, the samples were collected from the lower brown moraine of the Dnjeperian Glaciation (Fig. 3a) and from the Makarovo and Yakovka exposures of the Kalininan moraines; moreover, the Makarovo section is represented by samples collected in different years (Fig. 3b, 3c). The study of the Chermenino section was carried out in detail, and a complex analysis of biostratigraphic, geomorphological, palynological, lithological and other data (Sudakova *et al.*, 1995) made it possible to distinguish here the moraine beds of the Dnjeperian, Moskowian (two beds divided by a layer of clay containing plant remains with interstadial characteristics), and Kalininan ages. Figs. 3e–3h show data on all four moraine beds.

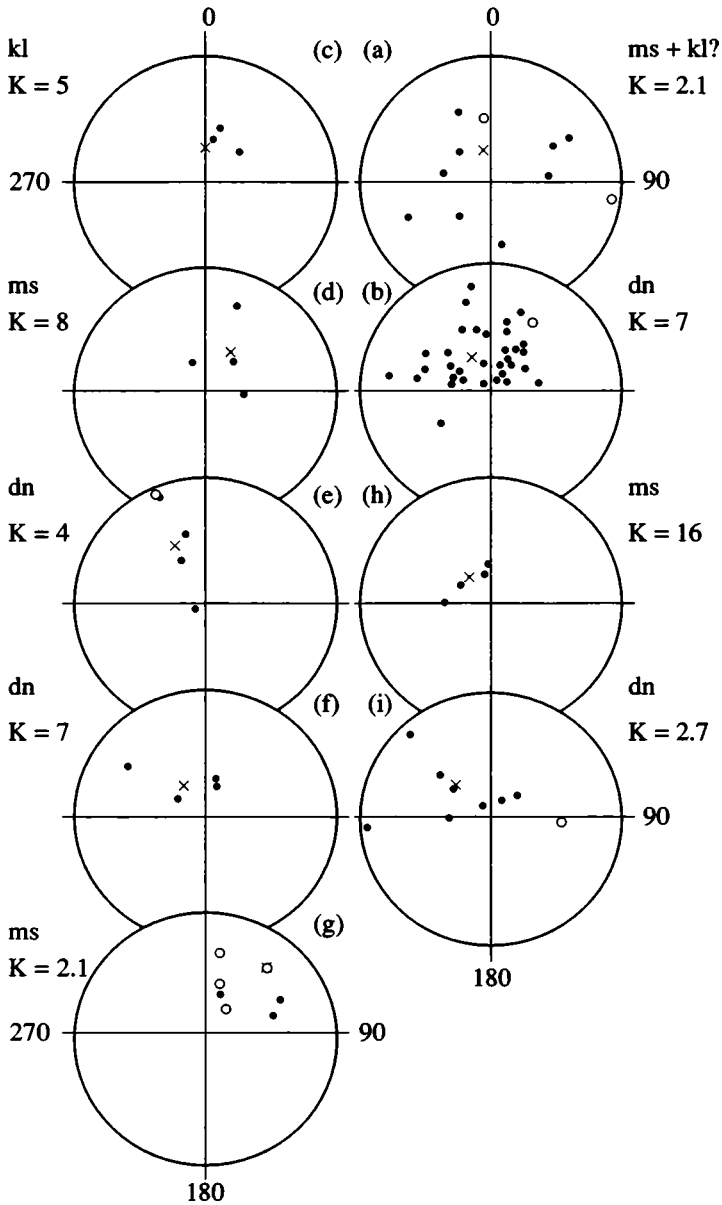

Fig. 2. Stereographic projections of magnetization vectors in moraines from sections: (a, b) Spas-Kamenki, (c–g) Cheremoshnik, (h, i) Shurskol.

Not long ago, the Narovatovo section in Mordovia was studied (Runkov *et al.*, 1993). Three moraine beds were distinguished on the basis of lithological features and magnetic properties. Researchers attributed these deposits to two glacial epochs: pollen of the Likhvinian Interglacial in the overlying bed allowed them to refer the upper red moraine to the Okaian glaciation and the lower moraine beds to the Don age. The paleomagnetic data on all three moraine beds are shown in Figs. 4a–4c. Most representative rock samples were collected with an interval of about 0.6 m from the upper (red) and lower (black) moraine beds. Intervals between rock samples in the middle part were more than one meter.

In the studied moraines, the main magnetic minerals are magnetite, maghemite, and hematite (Bol'shakov, 1984). In the samples, the value of the Koenigsberger Q factor is mainly within 0.1–1.0. The maximal value of Q factor (3.3) was recorded in one of the samples from the Moskowian moraine of the Semichevo section (Kaluga region). The Q values for other samples, however, are close to one. The samples have a relatively high content of hematite. The value of the viscose magnetization usually does not exceed 70% of I_n. The Wilson diagrams (WD), shown in Fig. 5 and obtained at the Paleomagnetic Laboratory of Kazan University, confirm these results. According to calculations based on the experimentally measured value of activation energy

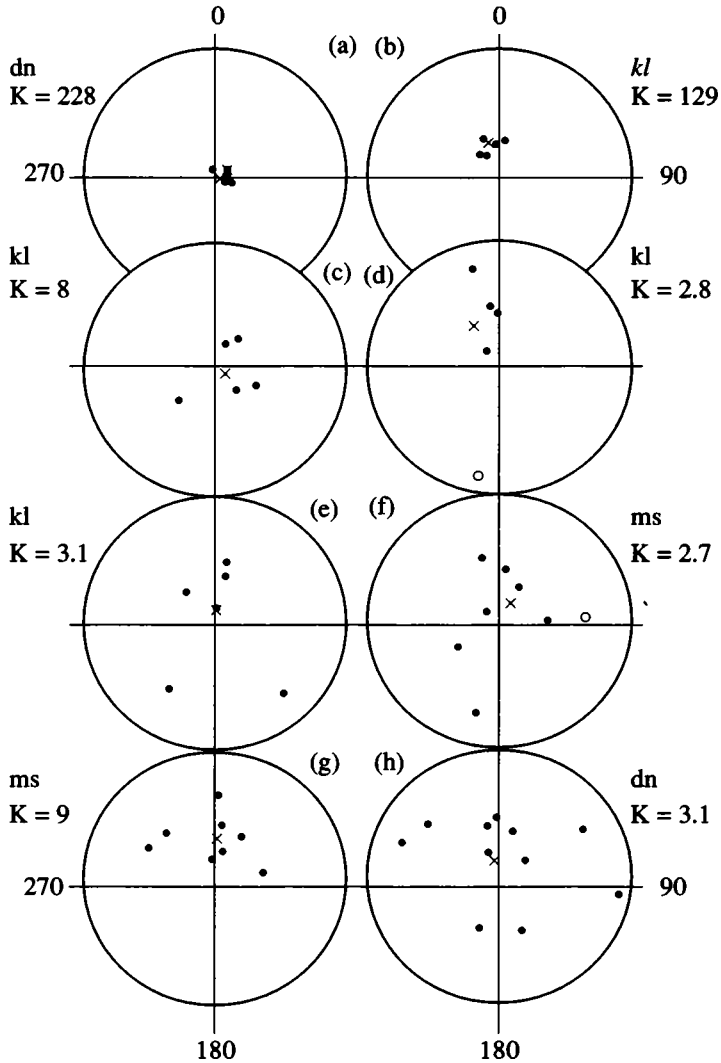

Fig. 3. Stereographic projections of magnetization vectors in (a) Pechegda, (b, c) Makarovo, (d) Yakovka, (e–h) Chermenino moraines.

(Bol'shakov and Faustov, 1976), the viscose magnetization, under continuous heating, should be cleaned off at 300°C. The WD for the oriented sample from clearing 205 in the Cheremoshnik section of the Dnjeperian moraine (Fig. 5a) demonstrates three magnetization components, whose vectors are shown by arrows and represent the total magnetization of the sample. Other WD (Fig. 5b–5d) are plotted for samples from wells P-3 (the moraine is determined to be transitional from the Dnjeperian to Moskowian), M-3, and G-10 (their moraines are dated back to the Moskowian age), all drilled in the Satino Test Area. The samples from wells are not oriented, and the figures show only Z axes of the samples. The question mark near the arrow in Fig. 5b indicates that the identified I_n component should rather be considered as fictitious and resulting from the transition from the primary magnetization vector to the vector measured after heating to $T = 600$°C.

DISCUSSION

The materials presented here differ from the results of other researchers primarily by the revealed negative inclination and a wide scatter of I_n vector in samples from some sections of the Moskowian and Kalininan moraines (Figs. 1d–1f, 2a–2g, and 3c–3f). The data presented also indicate the normal polarity of the Dnjeperian, Okaian and Don moraines in contrast to many published data, including those in my own publications. For example, the Okaian moraine has the anomalous (my data for the Tarusa Section in Sudakova *et al.*, 1982), or normal I_n vectors (Figs. 1a, 4a). In all the samples I studied, including those missing in this paper (except one (Fig. 1b) from the Dnjeperian moraine), the average magnetization vector also has a positive inclination angle. Only one sample from the Moskowian moraine, as in the case of the Dnjeperian moraine, showed a summary angle of J_{av} less than zero (Fig. 2g).

The magnetization vectors of samples from the Kalininan moraine, though sometimes anomalous, are also characterized by positive J_{av} values. In general, the data under discussion mainly display the low cluster values ranging from 1.3 to 16, though there are few high K values: 228 for the Dnjeperian and 129 for the Yaroslavl (Volga River) moraines (Figs. 3a, 3b).

The earlier publications likewise discussed the cases of normal (and also reversed) polarity of magnetization in moraines (Zubakov and Kochegura, 1973; Gaigalas and Pevzner, 1976; Lazukov *et al.*, 1982). However, these facts either were not considered, or the interpretation was assuming that the negative J values, or D values inside the 90°–180°–270° interval when $J > 0$ suggest the presence of the reversed I_n component (Lazukov *et al.*, 1982; Faustov, 1986, pp. 51–52). According to this interpretation, the data described here should indicate the reversed initial magnetization of moraines of the Moskowian and Kalininan ages. This conclusion seems improbable for several reasons. First, both the published data and the evidence given in this paper indicate the direct polarity of magnetization of moraines of the Moskowian and Kalininan glaciations. Second, the Blake excursion, which is the closest in time to the epoch of the Moskowian Glaciation, corresponds to the Mikulino Interglacial (Pospelova, 1989; *Stratigrafiya ...*, 1992). Third, the next Kargapolovo excursion is also confined not to the Kalininan Glaciation, but to the interstadial Monchalov Horizon. Therefore, the supposition that there is a global link between magnetic excursions and glacial epochs, sometimes expressed in oral communications, is not confirmed by the latest data.

Therefore, considering the direct polarity of the Moskowian and Kalininan moraines, we should assume that the great scatter of I_n vectors may not be associated with the remagnetization of reversely magnetized rocks in the field of normal polarity. In fact, the actual mechanism of appearance of stable secondary magnetization in moraines is, strictly speaking, not established. The viscose magnetization (Trukhin, 1969; 1977) is unstable with regard to temperature effects. As shown earlier (Bol'shakov and Faustov, 1976), almost 90% of the viscose magnetization formed during the Bruhnes Chron can be destroyed at 220°C during two hours. Consequently, I should emphasize that as yet, the possibility of the secondary magnetization of moraines, for example, by the freezing–thawing processes, and especially the characteristics of the corresponding magnetization (stability, value, vectors) can be considered only as conjecture. The data illustrating that the distribution of the I_n vector is variable in the same moraine beds even with short distances between the sampling points implies a considerable instability of sedimentation environments. The most spectacular example is the Makarovo section (Figs. 3b, 3c), where clearings were located in one quarry. This section apparently suggests variations in sedimentation environments from favorable to unfavorable for the magnetic particle orientation in the magnetic field. These conditions can be influenced by various natural factors, such as the dynamic activity of the glacier, the amount of water in the moraine, the possible chemical changes (Lavrushin, 1976), the size of magnetic particles or of the nonmagnetic grains containing them, the previously mentioned freezing–thawing process. From this viewpoint, the application of redeposition factor (Goncharov, 1965; Isaeva *et al.*, 1978) lacks sufficient grounds to draw conclusions about the mechanism of magnetization of moraines. Naturally, the variety of conditions and factors affecting magnetization can be assumed for a moraine of any age. But then, for example, how should we account for the systematically greater scatter of I_n vectors in samples of the Dnjeperian moraine as compared to the Moskowian moraine in the Satino Test Area?

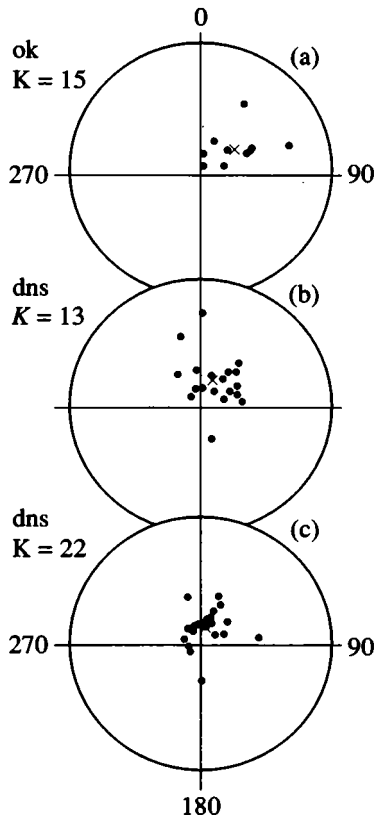

Fig. 4. Stereographic projections of magnetization vectors in the Narovatovo section: (a) upper, (b) middle, (c) lower moraine beds.

The following reasoning is an attempt to explain this situation. It is obvious that one of the factors unfavorable for the orientation of magnetic particles in the field is the increase of these particles in size, and it should be effective with respect to the moraine deposits (Ryabushkin and Pevzner, 1978). To my mind, this point of view is positively confirmed by the Wilson's diagrams shown in Fig. 5. For example, the WD for the Dnjeperian moraine from the Cheremoshnik section

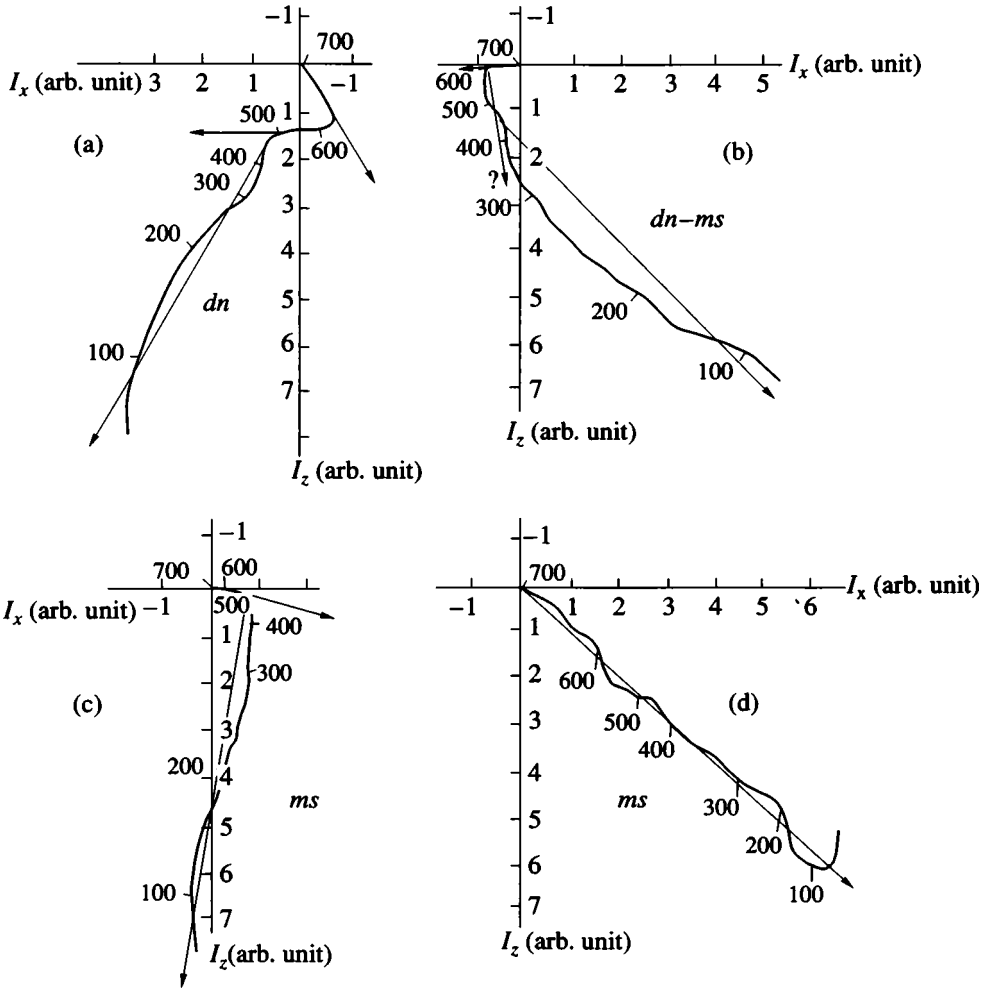

Fig. 5. Wilson diagrams for moraines in sections: (a) Cheremoshnik, clearing 205; (b, c, d) Satino, wells P-3, M-3, G-10; (temperature marks in degree centigrade).

can be interpreted as follows. Up to T = 500°C, only that part of magnetization is "cleaned off" that is directed along the modern field and related to the viscose component, i.e., to the probable chemical magnetization of hydroxides, and to maghemite and small magnetite and hematite grains, whose blocking temperature is less than 500°C. It is generally known that small particles are not as resistant to the temperature effect as the larger grains which exceed the size of the monodomains. The irregular magnetization that remains after heating up to 500°C can be attributed to the effect of large magnetite (the temperature interval from 500°C to 600°C) and hematite (over 600°C) particles, which are not oriented along the EMF vector. It should be mentioned, that the degree of particle orientation in the magnetic field can be determined not only by its own dimensions, but also by the dimensions of the nonmagnetic matrix incorporating the particle. In a similar way, I interpret the WD from the moraine samples from the Satino Test Area (Figs. 5b–5d). I should note the monocomponent magnetization in one of the samples from the Moskowian moraine (Fig. 5d), which, probably, indicates the absence of large unoriented magnetic particles. This observation provides one of the explanations for the generally different character of distribution of I_n vectors in the samples of the Moskowian and Dnjeperian moraines at the Satino Test Area. In the Dnjeperian moraine, the relative number of large magnetic particles chaotically oriented with respect to the EMF vector is on average greater than that in the Moskowian moraine. This interpretation is also corroborated by data on the distribution of magnetic susceptibility of moraine fractions from the test area (Bol'shakov, 1989). This means that the χ value of the Moskowian moraine is determined by the smallest fractions of 0.1–0.01 mm and less than 0.01 mm in size, whereas in the Dnjeperian moraine parameter χ is more regularly distributed mainly in fractions of 0.5–0.25 mm, 0.25–0.1 mm, and less than 0.01 mm in size. Moreover, the χ value of the Moskowian moraine at the Satino Test Area is on average twice as high as that of the Dnjeperian moraine. Therefore, the magnetite content, which

mainly determines the χ value, is less in the Dnjeperian moraine than in the Moskowian moraine. Consequently, there are reasons to suggest the relatively great role of hematite in the magnetization of the Dnjeperian moraine. As can be inferred from the Wilson's diagrams, it is actually hematite that is more often the carrier of the irregular I_n component.

Perhaps, another fact should be mentioned here to justify the suggested explanation. When studying the applicability of the determination criterion for the domain structure (Bol'shakov and Vinogradov, 1989), we used a moraine sample from the Makarovo section, because it had a high magnetic susceptibility value χ more than 50×10^{-6} CGS. We were surprized to find that the sample was rich in those small magnetic particles whose size was close to that of the monodomain particle. This sample is actually one of a series that had K=129, unusual for the moraines in our collection.

There is another explanation for differences in the distribution of I_n vectors, namely the lower water content in the Dnjeperian moraine that hinders the orientation of magnetic particles along the field. The validity of the last supposition, however, cannot be assessed without supplementary paleogeographic data. The main hazards in the study of natural objects is the situation in which even the basic factors that define a certain phenomenon cannot be reliably determined. Therefore, the suggested variants do not cover all the complexities of the paleomagnetic studies of moraines. As noted above, this problem is connected with such global and unsolved issues as the stratigraphy and correlation of glacial beds and the quantity and stratigraphic allocation of geomagnetic excursions in the Bruhnes Chronozone, to say nothing of their absolute age determinations. It is also surprising that the geomagnetic excursion is often discovered in the Dnjeperian moraine, e.g., one scientific team (Isaeva *et al.*, 1978) recorded it at 75 sites in the moraines, where the selection of oriented samples is extremely difficult and makes the sampling of the entire glacial bed practically impossible. On the other hand, in the Dnjeperian loess, which is the much more favorable object for paleomagnetic research and the stratigraphic analogue to the Dnjeperian moraine in areas free of glaciation, the excursion is substantiated only in the fourth part of sections of this bed subjected to paleomagnetic study (Veklich, 1982; p. 166). Probably, one of the reasons for the frequent determination of magnetic excursions in the Dnjeperian moraine was the large-amplitude variable magnetic field (800–1200 oersted) used to reveal the initial magnetization (Desyatova *et al.*, 1973; Trukhin, 1977). This field is sufficient for the almost complete demagnetization of the magnetite component, because the coercive force of the monodomain magnetite particles is about 400 oersted (Bol'shakov and Vinogradov, 1989). The remaining hematite grains, owing to their low magnetization and less regular orientation in the field, reduce the accuracy of I_n measurements. The magnetic biasing is another unfavorable factor in the application of the variable (industrial frequency) large-amplitude magnetic field for magnetic cleaning, because it is usually inevitable when the field values are more than 200 oersted (Faustov *et al.*, 1986).

The interpretation of the obtained paleomagnetic data is likewise hindered by insufficient information on the time intervals of accumulation (sedimentation rate) of the studied glacial beds. All these reasons lead to the conclusion that, on the whole, the moraines are unfavorable objects for traditional paleomagnetic studies and especially for the identification of stratigraphically important horizons of anomalous (reversed) magnetization induced by geomagnetic excursions. The high scatter of I_n vectors in samples from the Moskowian and Kalininan moraines (I consider these deposits as normally magnetized) indicates that ancient moraines are not specific objects for paleomagnetic analysis. As suggested earlier (Ryabushkin and Pevzner, 1978), the approach should be identical for moraines of various ages and based on the statistical processing of paleomagnetic data. The results of this processing presented here confirm the conclusion of aforementioned authors that, in the moraines, the average $\bar{R}$ value (the absolute value of the average magnetization vector in the sample collection normalized to the number of samples) is in most cases more than 0.5. While using the curve of critical $\bar{R}$ values from the cited work, I was convinced that more than 80% of my data satisfy the Rayleigh criterion, thus indicating the presence of the systematic magnetization component in most of the studied moraine beds. At the same time, the results of calculations of I_n vectors suggesting the negative (with $J < 0$ value) of magnetization of samples (Figs. 1a, 1b, 1d; 2g; and 3d) do not satisfy this criterion. These data show that there are no grounds to speculate on the reversed (anomalous) magnetization in the studied moraines. Naturally, this conclusion can be true only if the initial I_n component prevails in the analyzed magnetization parameters. I think that the nature of this magnetization is sedimentary, but complicated by specific conditions of glacial lithogenesis. This viewpoint is confirmed, firstly, by clusters of I_n vectors with low K values, which are concentrated around the direction toward the modern pole and, secondly, by the low Q factor in the moraine samples. The analysis of WDs (Fig. 5) shows that no less than 50% of I_n vectors correspond to the regular magnetization induced by the orientation to the modern pole. Consequently, this actually determines values of the Q factor typical of sedimentary magnetization.

I consider problematic the calculation of the virtual geomagnetic pole (VGP) position using data on moraines and more precise formulas (Ryabushkin and Pevzner, 1978) instead of the usually applied formulas. This conclusion was reached by the following reasonings:

(1) In the case of the "remagnetized" moraine, the VGP calculations are, evidently, meaningless, because

we do not know the remagnetization mechanism, what kind of process took place or for how long, and at what stage the secondary magnetization was fixed, etc. In other words, we do not know with what factor to correlate the VGP direction, either with the ancient EMF vector, or with the summary vector of the initial and secondary magnetization fixed at a certain stage of remagnetization.

(2) In moraines, the magnetization vector can reflect not only the EMF, but, as shown by Faustov *et al.* (1986), also the direction of movement of the glacier and, probably, other factors of glacial sediment genesis.

(3) The accuracy of determination of the VGP position by using data on moraines is usually low, and a higher accuracy would require a considerably greater amount of work without an assurance of positive results. In this paper, the radius of the confidence circle for the average I_n vectors is mainly within 18°–41°, and only in five cases α_{95} was less than 15°.

The above reasoning lead to the conclusion that, in the paleomagnetic study of moraines, the most effective is the determination of polarity of their magnetization by standard methods (Khramov and Sholpo, 1967) by using the Rayleigh criterion.

The results of paleomagnetic studies of Pleistocene moraines in the European part of Russia show frequent distortions of paleomagnetic records in the moraine deposits accumulated in the normal EMF. Since the normal field was dominant in the Pleistocene, we may conclude that paleomagnetic records in the Pleistocene moraines, which were formed in the period of a reversed (anomalous) geomagnetic field, should be distorted to a still greater degree. As a result, the differences between the normally magnetized and initially reversely magnetized moraines should not be very distinct. Thus, the determination of geomagnetic excursions in a moraine bed is a challenging problem. To solve it, a meticulous study of both the thickness and strike of the moraine bed is required. This research should be carried out with a unified technique and would be unproductive without reliable stratigraphic substantiation. Therefore, let us consider once more the stratigraphy of studied deposits. In the Yaroslavl region, the interpretation of the Kalininan moraine, which is closest to the surface and overlies the Mikulino deposit being overlain by the upper loesslike loams, is sufficiently justified (Sudakova, 1990). Below this moraine, there is the red-colored moraine, which is also the closest to the surface in many sections we studied in the Yaroslavl, Moscow and Kaluga regions. Displaying persistent lithological and magnetic characteristics, the respective bed is reliably interpreted as the Moskowian moraine. The disagreement in opinions concerns the underlying Dnjeperian and Okaian moraines. But in the context of this paper it is important to note that these moraine beds are much older than the Moskowian moraine, and that each of them, particularly the Dnjeperian bed, is determined in the studied regions as an independent stratigraphic horizon (Sudakova, 1990). It is also important to note that the moraine deposits under discussion are comparable in magnetic parameters with moraines studied in the same regions by other authors. None of these four or five moraines of different ages, including the Don moraine of the Narovatovo section, is found to have the reversed magnetization in contrast to previous results of their interpretation published by many researchers, including my own.

CONCLUSION

1) The paleomagnetic anomalies in the early and middle Pleistocene moraines, interpreted as excursions by many researchers, can in fact be associated with specific conditions of magnetization in these deposits usually causing a considerable scatter of the magnetization vector.

2) My studies of the Pleistocene moraines ranging from the Don to Kalininan ages did not reveal the reversed magnetization in these deposits. The statistically significant evidence indicates only the normal polarity of magnetization in the studied moraines.

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REFERENCES

Bol'shakov, V.A., Application of Some Magnetic Parameters to Subdivide Heterochronous Moraines, in *Paleomagnitnaya stratigrafiya mezo-kainozoiskikh otlozhenii* (Paleomagnetic Stratigraphy of Mesozoic–Cenozoic Deposits), Kiev: Naukova Dumka, 1982, pp. 68–72.

Bol'shakov, V.A., Some Results and Problems of Studies on the Pleistocene Moraines by Using Rock Magnetism, *Vestn. Mosk. Univ., Ser. Geogr.*, 1984, no. 3, pp. 63–68.

Bol'shakov, V.A., On Using Rock Magnetism in Studies on Recent Deposits, in *Chetvertichnyi period: stratigrafiya* (Quaternary Period: Stratigraphy), Moscow: Nauka, 1989, pp. 213–220.

Bol'shakov, V.A. and Faustov, S.S., On Thermomagnetic Cleaning, *Izv. Akad. Nauk SSSR, Fizika Zemli,* 1976, no. 3, pp. 116–120.

Bol'shakov, V.A. and Faustov, S.S., *Magnitnye svoistva i paleomagnetism noveishikh otlozhenii basseina Srednei Protvy* (Magnetic Properties and Paleomagnetism of Recent Deposits in the Middle Protva River Basin), Available from VINITI, Moscow, 1979, issue 3, no. 1893-79, pp. 110–130.

Bol'shakov, V.A. and Vinogradov, Yu.K., Heating–Free Methods of Determination of the Domain Structure, in *Issledovaniya v oblasti paleomagnetizma i magnetizma gornykh*

porod (Studies on Paleomagnetism and Magnetism of Rocks), Moscow: Nauka, 1989, pp. 55–72.

Desyatova, T.F., Karpukhin, S.S., Sudakova, N.G., and Trukhin, V.I., Age Criteria for Moraines in the Volga Region near Yaroslavl, *Dokl. Akad. Nauk SSSR,* 1983, vol. 213, no. 3, pp. 657–660.

Eremin, V.N., Makarov, V.A., and Molostovskii, E.A., Results of Preliminary Paleomagnetic Studies on Quaternary Deposits in the Volga Region near Saratov, in *Materialy 9 konferentsii po voprosam postoyannogo geomagnitnogo polya* (Proc. 9th Conf. on Problems of the Permanent Geomagnetic Field), Baku: Akad. Nauk SSSR, 1973, pt. 3, pp. 70–71.

Faustov, S.S., Specific Aspects of Paleomagnetic Studies on Moraines, in *Kompleksnoe izuchenie opornykh razrezov nizhnego i srednego pleistotsena evropeiskoi chasti SSSR* (Multipurpose Studies on the Lower–Middle Pleistocene Reference Sections in the European Part pf the USSR), Moscow: Geolfond SSSR, 1981, pp. 124–127.

Faustov, S.S., Bol'shakov, V.A., Virina, E.I., and Demidenko, E.L., Methods of Using Rock Magnetism and Paleomagnetism in Studies on the Pleistocene, *Itogi nauki i tekhniki, Paleogeografiya,* Moscow: VINITI, 1986, vol. 3.

Faustov, S.S., Il'ichev, V.A., and Bol'shakov, V.A., Results of Paleomagnetic and Thermomagnetic Investigations of the Likhvinian Section, *Dokl. Akad. Nauk SSSR,* 1974, vol. 214, no. 5, pp. 1160–1162.

Gaigalas, A.I. and Pevzner, M.A., Paleomagnetic Studies on Glacial Deposits, in *Glavnoe geomagnitnoe pole i problemy paleomagnetizma* (Main Geomagnetic Field and Problems of Paleomagnetism), Moscow: Inst. Fiziki Zemli Akad. Nauk SSSR, 1976, pt. 3, p. 26.

Goncharov, G.I., Potentialities of the Paleomagnetic Method in Solving Problems of Quaternary Geology, in *Nastoyashchee i proshloe magnitnogo polya Zemli* (Current and Past State of the Magnetic Field of the Earth), Moscow: Nauka, 1965, pp. 227–233.

Hus, J.J. and Geeraerts, R., Palaeomagnetic and Rock Magnetic Investigation of Late Pleistocene Loess Deposits in Belgium, *Phys. Earth. Planet. Inter,* 1986, vol. 44, pp. 21–40.

Isaeva, M.I., Sudakova, N.G., and Trukhin, V.I., Recognition and Correlation of the Okaian and Dnjeperian Moraines in Central Russia, *Vestn. Mosk. Univ., Geologiya,* 1978, no. 1, pp. 117–120.

Khramov, A.N. and Sholpo, L.E., *Paleomagnetizm* (Paleomagnetism), Leningrad: Nedra, 1967.

Kulikov, O.A. and Krasnenkov, R.V., Magnetostratigraphic Studies on Moraines of the Don Glacial Tongue, in *Glavnoe geomagnitnoe pole i problemy paleomagnetizma* (Main Geomagnetic Field and Problems of Paleomagnetism), Moscow: Inst. Fiziki Zemli Akad. Nauk SSSR, 1976, pt. 3, p. 60.

Kulikov, O.A., Trukhin, V.I., and Faustov, S.S., About the New Reversal of the Geomagnetic Field during the Maximum Glaciation Epoch, in *Postoyannoe magnitnoe pole Zemli, paleomagnetizm i magnetizm gornykh porod* (Permanent Magnetic Field of the Earth, Paleomagnetism, and Rock Magnetism), Kiev: Naukova Dumka, 1973, pp. 45–47.

Lavrushin, Yu.A., *Stroenie i formirovanie osnovnykh moren materikovykh oledenenii* (Structure and Formation of Main Moraines during the Continental Glaciations), Moscow: Nauka, 1976.

Lazukov, G.I., Sudakova, N.G., and Faustov, S.S., An Analysis of Glacial Deposits in the Klin–Dmitrov Rise: Implications for Problems of Stratigraphy and Paleogeography, in *Noveishaya tektonika, noveishie otlozheniya i chelovek* (Neotectonics, Recent Deposits, and Man), Moscow: Mosk. Gos. Univ., 1982, pp. 86–100.

Pospelova, G.A., Magnetic Excursions as the Chronological Reference Levels for Quaternary Deposits, in *Chetvertichnyi period: stratigrafiya* (Quaternary Period: Stratigraphy), Moscow: Nauka, 1989, pp. 196–203.

Putevoditel' ekskursii Moskva–Verkhnyaya Volga (Guide Book to Excursions from Moscow to Upper Courses of the Volga River), Markov, K.K., Ed., Moscow: Mosk. Gos. Univ., 1969.

Runkov, S.I., Bol'shakov, V.A., Nemtsova, G.M., *et al.,* The Pleistocene Reference Section of the Village of Narovatovo, the Moksha River, in *Byull. Regional'noi mezhvedomstvennoi stratigraficheskoi komissii po tsentru i yugu Russkoi platformy* (Bull. Interdept. Stratigr. Commission on the Central and Southern Russian Platform), Moscow: Mezhved. Stratigr. Kom. Rossii, 1993, pp. 144–152.

Ryabushkin, P.K. and Pevzner, M.A., Statistics of Highly Dispersed Directions Inferred by Studies on Remnant Magnetisation of Moraines, *Izv. Akad. Nauk SSSR, Fizika Zemli,* 1978, no. 12, pp. 103–106.

Semenov, V.V., Geomagnetic Excursions of the Brunhes Chron in the Pleistocene Deposits of the Central Russia, in *Vserossiiskoe soveshchanie po izucheniyu chetvertichnogo perioda* (All-Russia Conf. on the Investigation of the Quaternary Period), Moscow: Ross. Akad. Nauk, 1994, p. 215.

Stratigrafiya i paleogeografiya chetvertichnogo perioda Vostochnoi Evropy (Quaternary Stratigraphy and Paleogeography of Eastern Europe), Velichko, A.A. and Shik, S.M., Eds., Moscow: Inst. Geogr. Ross. Akad. Nauk, 1992.

Sudakova, N.G., *Paleogeograficheskie zakonomernosti lednikovogo litogeneza* (Paleogeographic Trends in the Glacial Lithogenesis), Moscow: Mosk. Gos. Univ., 1990.

Sudakova, N.G. and Bol'shakov, V.A., The Oldest Moraine near the Town of Chekalin, the Oka River, *Dokl. Akad. Nauk SSSR,* 1977, vol. 233, no. 6, pp. 1176–1179.

Sudakova, N.G., Bol'shakov, V.A., Boyarskaya, T.D., *et al.,* The New Tarusa Section of Quaternary Deposits, in *Dokl. Akad. Nauk. SSSR,* 1982, vol. 267, pp. 909–912.

Sudakova, N.G., Gunova, V.S., and Nemtsova, G.M., The Middle–Late Pleistocene Stratigraphy and Paleogeography in the Rybinsk–Yaroslavl Region, *Stratigr. Geol. Korrelyatsiya,* 1996, no. 2, pp. 46–55.

Trukhin, V.I., The Natural Remnant Magnetization of Quaternary Moraines, in *Magnetizm gornykh porod i paleomagnetizm* (Rock Magnetism and Paleomagnetism), Moscow: Inst. Fiziki Zemli Akad. Nauk SSSR, 1969, pp. 92–93.

Trukhin, V.I., Paleomagnetic Investigation of Pleistocene Moraines, in *Razrezy otlozhenii lednikovykh raionov Tsentra Russkoi ravniny* (Sections of Glacial Deposits in the Central Russian Plain), Moscow: Mosk. Gos. Univ., 1977, pp. 44–45.

Veklich, M.F., *Paleoetapnost' i stratotipy pochvennykh formatsii verkhnego kainozoya* (Paleostages and Stratotypes of the Upper Cenozoic Soil Formations), Kiev: Naukova Dumka, 1982.

Verozub, K.L. and Banerjee, S.K., Geomagnetic Excursions and Their Paleomagnetic Record, *Rev. Geophys. Space Phys.*, 1977, vol. 15, no. 2, pp. 145–155.

Zubakov, V.A. and Kochegura, V.V., Chronology of the Recent Stage in Geological History of the USSR, in *Khronologiya pleistotsena i klimaticheskaya stratigrafiya* (The Pleistocene Chronology and Climatostratigraphy), Leningrad: Geograf. Obshchestvo SSSR, 1973, pp. 39–73.

Stratigraphy and Geological Correlation, Vol. 5, No. 6, 1997, pp. 615–619. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 5, No. 6, 1997, pp. 96–100.
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BRIEF COMMUNICATIONS

Diversity Dynamics of Silurian Gastropods as Related to Abiotic Events

A. P. Gubanov

Joint Institute of Geology, Geophysics, and Mineralogy, Siberian Division, Russian Academy of Sciences, Universitetskii pr. 3, Novosibirsk, 630090 Russia

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Paleozoic, particularly Silurian gastropods, were for a long time ignored by researchers though these organisms played a significant role in past ecosystems, and therefore are important for the assesment of the influence of abiotic factors on the benthic communities. Previously, the connection of the intraspecies variability of gastropods with hydrodynamics and the depth of the basin was established (Gubanov, 1985).

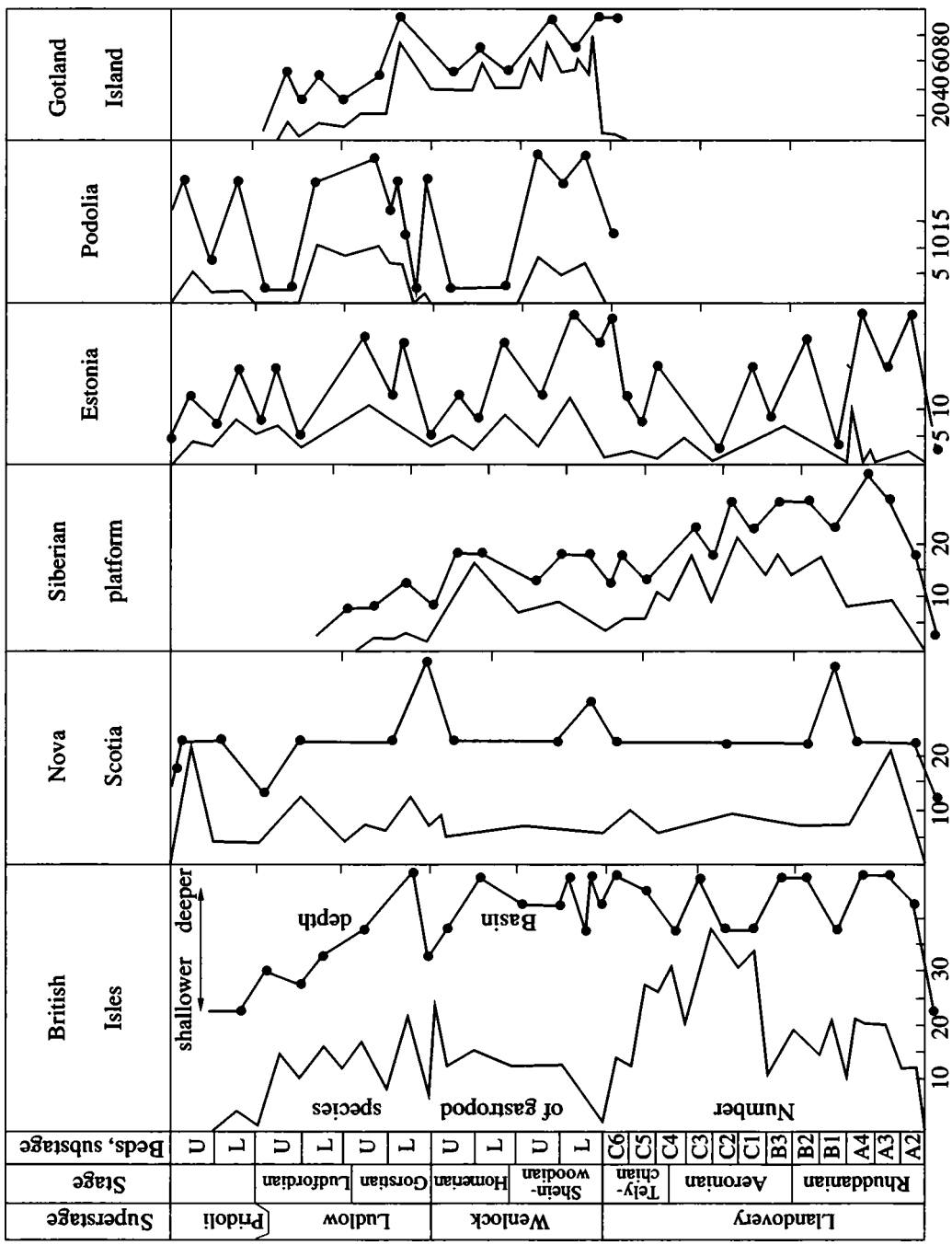
Stratigraphic distribution of Silurian gastropods in sections of the British Isles (Murchison, 1839; Donald, 1899, 1902, 1905, 1906; Longstaff, 1909; Reed, 1920, 1921; Pitcher, 1939), Nova Scotia (Peel, 1977), Eastern Siberia (Gubanov, 1985, 1988, 1992; Gubanov and Yochelson, 1994), Estonia (Isakar *et al.*, 1990), Gotland (Lindstrom, 1889; Peel and Wanberg-Eriksson, 1979), and Podolia (Mironova, 1987) served as basis to investigate changes in gastropod diversity with time and to study the probable connections of these changes with abiotic events, in particular with the sea-level changes and depth variations in paleobasins. This was preceded by the important preparatory arrangement of all available data in accordance with the recent stratigraphic scale. Some difficulties, which have not yet been overcome in the case of the Barrandian of the Prahian basin and some areas of North America where Silurian gastropods are well studied, are related to their indefinite stratigraphic distribution in particular sections. Therefore, only those sections were selected for investigation where Silurian gastropods are best studied and their stratigraphic position is doubtless. Based on published data, I analyzed the stratigraphic distribution of 129 gastropod species in the British Isles, 64 species in Nova Scotia, 74 species in Estonia, 26 species in Podolia, and 173 species in Gotland Island. Data on eastern Siberia are from my collection and were sampled from more than 200 outcrops and boreholes in the Siberian platform during 1980–1994. The collection includes about 6000 specimens of gastropod shells. The gastropod assemblage from Silurian deposits of eastern Siberia ammounts to 44 species (Gubanov, 1988, 1992).

The comparison of the diversity curves compiled for different regions and based on the gastropod stratigraphic distribution shows that most significant changes are confined to the boundaries between major stratigraphic units (Figure).

Most significant reorganizations in the gastropod assemblages occurred at the Ordovician–Silurian boundary. The Ordovician biotic crisis, one of the largest in history, resulted in the almost complete renovation of gastropods at the species level. Some species probably survived this crisis: however, we have only poor data on gastropods from the boundary strata. In addition, many Ordovician–Silurian boundary sections are represented only by the deep-water facies virtually lacking gastropods, whereas the Upper Ordovician deposits in more shallow-water sections are eroded. All these facts do not permit the precise assesment of the boundary species distribution.

At present, views on the connection of the biotic crisis with the largest Late Ordovician glaciation and, as a result, with a significant sea-level fall and reduction of sea areas seem to be most substantiated. The subsequent warming resulted in the sharp sea-level rise at the beginning of the Early Silurian (McKerrow, 1979; Brenchley, 1988). The major "anoxic event," which resulted in the formation of thick sequences of "black" limestones and graptolite shales at the base of the Silurian section, was related to this level (Berry and Wilde, 1978; Jeppsson, 1990).

The next significant reorganization in the gastropod community occurred at the Llandoverian–Wenlock boundary. In different regions, it was expressed in different modes. In the British Isles and eastern Siberia, the renovation of gastropod assemblages was accompanied by a significant reduction of their diversity in the late Llandovery, and then by a considerable speciation in the early Wenlock. In the sections of Estonia, Gotland, and Podolia, the gastropod diversity bursted in the early Wenlock and was significantly higher than that in the Llandovery. The Nova Scotia sections also show



Variations in the gastropod diversity and relative basin depth during the Silurian in the British Isles, Nova Scotia, Gotland (data by McKerrow, 1979), Estonia (data by Kyrts *et al.*, 1991), Podolia (data by Gritsenko *et al.*, 1986), and eastern Siberia (numbers indicate the abundace of gastropod species).

changes in diversity of gastropod assemblages, though they are insignificant there.

The Wenlock–Ludlow boundary was marked by the extinction of gastropods, and their diversity significantly lowered in Britain and eastern Siberia. These changes were less pronounced in Nova Scotia and Estonia (figure). In Podolia, the complete gastropod extinction occurred somewhat earlier, in the middle Wenlock. In Gotland Island, the species diversity did not change in the late Wenlock, however, the number of gastropod species increases almost twofold during a short period of the early Ludlow. A significant diversity increase also occurred at this time in the British Isles, Nova Scotia, and Estonia. Several new gastropod species also first appeared in Podolia, though the sharp increase in gastropod diversity occurred there somewhat later. In the Siberian platform, two gastropod species that survived the late Wenlock crisis were added by a single form, and all of them became extinct by the end of the Gorstian. Somewhat later, at the end of the Ludfordian, gastropods died out in Podolia, and their diversity was strongly reduced in Estonia and Gotland Island, where they experienced a brief episode of diversity increase followed by their complete extinction.

During the Pridoli time, gastropods continued to exist in British Isles where, after a significant late Ludlow reduction of diversity, they had a period of some diversification, which was followed by their complete extinction by the mid-early Pridoli. In Nova Scotia the number of gastropod species, after their twofold reduction in the late Ludlow, remained unchanged for a short period, and then, beginning from the middle Pridoli increased more than twofold. In Estonia, the Ludlow–Pridoli boundary was marked by the reduction of gastropod diversity, though not as significant as the preceding extinction at the Gorstian–Ludfordian boundary. In the early Pridoli, the gastropod diversity in the latter region increased for a short period. The upper Ludfordian deposits of Podolia lack gastropod remains. They appear there only in the early Pridoli, when their diversity gradually increased (figure).

Unfortunately, in those areas where gastropods evolved until the terminal Silurian, they are poorly studied, and, thus, the changes in their composition at the Silurian–Devonian boundary are unknown.

Changes in gastropod diversity were mostly related to the sea-level fluctuations and deepening of their habitat basins. Dependance on these factors is well seen from comparative curves of diversity changes, sea-level fluctuations, and basin depth variations plotted for different regions (figure). Data on changes of the sea level and basin depth during the Silurian are after McKerrow (1979) for British Isles, Nova Scotia, and Gotland, after Kyrts *et al.*, (1991) for Estonia, and after Gritsenko *et al.*, (1986) for Podolia. For the Siberian platform, I plotted such a curve using data on facial and faunal changes. In general, the diversity increase corresponds to the transgression time whereas its decrease is related to the regression and basin shallowing. This dependance of cyclic changes in gastropod assemblages on the sea-level fluctuations and changes in the basin depth is distinct. The general trend of sea-level changes during the Silurian shows it sharply rising in the early Llandoverian and gradually lowering during the entire Silurian. This trend is distinctly observed in sections of British Isles and eastern Siberia. The general sea-level lowering was complicated by cyclic changes of the lower rank. Four cycles, each corresponding respectively to the Llandovery, Wenlock, Ludlow, and Pridoli, can be distinguished in the Silurian; each of these cycles begins with a significant sea-level rise. The same periodicity is observed in reorganizations of gastropod communities.

In the British Llandoverian sections most thoroughly studied, four cycles of the second order can be observed in changes of the gastropod diversity.

The first cycle comprises the lowermost Rhuddanian (Beds A2–A4 of the British stratotype section) and terminates with the diversity reduction for 52%. Even more significant changes occurred at this level in Estonia (100%) and Nova Scotia (65%). The least diversity reduction (10%) was in Siberia.

The second cycle corresponds to the uppermost Rhuddanian–lowermost Aeronian (Beds B1–B3). It begins with the complete restoration of the gastropod diversity in British Isles; its increase was up to 70% in Estonia, and twice higher in Siberia. In Nova Scotia, the number of gastropod species remained at the previous level. The cycle terminated with the significant diversity reduction in Britain (43%) and eastern Siberia (22%). In Nova Scotia and Estonia, there were no changes in the gastropod diversity.

The beginning of the third cycle (middle Aeronian; Beds C1–C3) was marked by the threefold increase in the gastropod diversity in British Isles and for 50% in Siberia. The cycle terminated with an almost twofold decrease in diversity (49%) in British Isles. In other regions, this level does not mark changes. The most significant changes in the gastropod diversity in Estonia (the complete extinction of old species and the first appearance of five new species) and eastern Siberia (the extinction of 57% of species that was followed by the twofold increase of diversity) occurred somewhat earlier according to recent correlation schemes, whereas in Nova Scotia, changes in gastropod diversity (33% of extinct species and 40% of first appeared species) took place somewhat later than in British Isles.

The fourth, Llandoverian cycle is distinctly observed only in the British sections where they show the gastropod diversity for 30%-growth at the beginning of the cycle and their almost complete extinction of the Llandoverian species at the end. The upper boundary of the cycle, which simultaneously represents the boundary between cycles of the higher order, is distinctly traceable in all the regions in question.

The sea-level and basin depth changes during the Llandovery in British Isles, eastern Siberia, and Estonia show similar cyclic patterns, and this was evidently characteristic for most regions of the world (Johnson *et al.*, 1991). A somewhat different situation was in Nova Scotia. Here, the poorly expressed cyclicity is characteristic of changes in gastropod diversity, whereas no cyclicity in sea-level or basin depth fluctuations is observed. During the entire Silurian, the basin depth remained stable. Short-term deepenings of the basin in the middle Rhuddanian and at the Llandovery–Wenlock, Wenlock–Ludlow, and Ludlow–Pridoli boundaries were soon compensated by sedimentation.

The Wenlock was marked by a single cycle in the gastropod evolution. Changes in the gastropod community composition occurred at different levels in various regions. In the Homerian of British Isles, the gastropod diversity first decreased by 25% and then doubled. In Estonia, this event (the diversity decrease by 75% and fourfold increase) occurred in the late Sheinwoodian, whereas in Gotland (changes for 34% and 25% respectively) somewhat later. Renovation of the gastropod community in eastern Siberia (a decrease by 22% and a two-and-a-half-fold increase in gastropod diversity) and Podolia (complete extinction) took place at the Sheinwoodian–Homerian boundary. This level is also traced in Britain and Gotland, where it is expressed less distinctly. Like in the Wenlock, cycles of the lower order are also obscure in the Ludlow and Pridoli. Nevertheless, the dependence of the gastropod diversity on the sea-level fluctuations and basin depth is distinct.

An interesting peculiarity should be noted: the highest gastropod diversity in British Isles and the Siberian platform correlates with the termination of major cycles corresponding to the stratigraphic epochs, whereas in the southwestern and northwestern Russian platform (in Podolia, Estonia, and Gotland) it was at the initial stage of these intervals.

The coherence between changes in the Silurian gastropod diversity, sea-level fluctuations and changes in the basin depth in various regions of the world allows us to suggest the close interrelations between the diversity and processes that were responsible for fluctuations of the aforementioned factors.

The sea-level and depth changes were evidently related to the glacioeustasy as a result of changes in the Earth climate and its tectonic regime. The general regressive trend in the sea-level changes is related to the terminal stage of the Caledonian cycle (Seslavinskii, 1987, 1991) including the early Llandoverian transgression that corresponded to the Late Ordovician glacioeustatic event (McKerrow, 1979). Though the dependance of the gastropod diversity on these events seems to be doubtless, the mechanism of their influence on the gastropod community is not quite clear. It could be suggested that a certain optimum level of diversity should exist. By the sea-level and depth changes, this level could fluctuate, and this should be reflected in the the diversity curve. However, the curve in this case would be somewhat different because changes in diversity during the basin deepening or shallowing should be of the same type. On the other hand, one can hardly expect that benthic and planktonic organisms similarly reacted in response to possible events. Nevertheless, their reaction was similar to that confirmed by similar changes in the graptolite diversity (Melchin, 1994). In connection with the above, another mechanism causing diversity changes, which is known as a hypothesis of equilibrium suggested by MacArthur and Wilson (Hallam, 1983), seems to be more appropriate. During the sea-level lowering, areas of the shallow water marine basins were reduced. This was particularly true for marine basins of the platform type. This process resulted in the reduction of biotopes, which, in turn, led to the growth of the K-selection factor and eventually to diversity reduction. On the contrary, the increase of sea areas favored the appearance of new and the widening of previously existed biotopes, that stimulate the species diversification and radiation.

CONCLUSION

(1) The Silurian comprises four global gastropod diversity cycles whose boundaries correspond to the boundaries between superstages. Four cycles of the lower order are defined in the Llandovery. The causes responsible for these changes are not quite clear. Changes in the sea area size were probably the main factors which influenced diversity. The reduction of sea basins resulted in the reduction of biotopes that activated the biologic competition, whereas the increase in size was favorable for the emergence of new biotopes, competition weakening, and intense species radiation.

(2) Close interrelations between changes in the gastropod diversity and sea-level fluctuations are undoubted. Most significant events responsible for global changes of the sea level were: (a) glacioeustasy in the early Llandovery and (b) the terminal phase of the Caledonian tectogenesis that resulted in the regression of the Silurian basins.

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REFERENCES

Berry, W. and Wilde, P., Progressive Ventilation of the Oceans—an Explanation for the Distribution of the Lower Paleozoic Black Shales, *Am. J. Sci.*, 1978, vol. 278, pp. 257–275.

Brenchley, P., Environmental Changes Close to the Ordovician—Ilurian Boundary, *Bull. Brit. Mus. Nat. Hist,* 1988, vol. 43, pp. 377–385.

Donald, J., Remarks on the Genera *Ectomaria* Koken, and *Hormotoma* Salter, with Descriptions of British Species, *Quart. J. Geol. Soc. London,* 1899, vol. 55, pp. 251–272.

Donald, J., Proterozoic Murchisoniidae, Pleurotomariidae and Turritelliidae, *Quart. J. Geol. Soc. London,* 1902, vol. 58, pp. 313–339.

Donald, J., On Some Gastropods from the Silurian Rocks of Llangadock, *Quart. J. Geol. Soc. London,* 1905, vol. 61, pp. 567–577.

Donald, J., Notes on the Genera *Omospira, Lophospira,* and *Turritoma,* with Descriptions of New Proterozoic Species, *Quart. J. Geol. Soc. London,* 1906, vol. 62, pp. 552–572.

Gritsenko, V.P., Ishchenko, A.A., and Konstantinenko, L.I., An Experience in Reconstructing the Yagur and Malinovtsy Benthic Communities (Silurian of Podolia), in *Teoriya i opyt ekostratigrafii* (Theory and Practice of Ecostratigraphy), Tallinn: Leningrad. Gos. Univ., 1986, pp. 73–79.

Gubanov, A.P., Changeability of Gastropod as Dependent on the Basin Hydrodynamics, in *Sreda i zhizn' v geologicheskom proshlom. Paleobasseiny i ikh obitateli* (Environments and Life in the Geological Past: Paleobasins and Their Dwellers), Novosibirsk: Nauka, 1985, pp. 70–74.

Gubanov, A.P., Silurian Gastropods from the Siberian Platform: Taxonomic, Paleoecologic, and Biostratigraphic Analyses, *Cand. Sci. (Geol.-Mineral.) Dissertation,* Novosibirsk: Inst. of Geology and Geophysics, Siberian Division, USSR Acad. Sci., 1988.

Gubanov, A.P., Silurian Gastropods from the Lower Bol'shaya Kuonda Reference Section, in *Razrezy i fauna silura severa Tungusskoi sineklizy* (Silurian Fauna and Sections in the Northern Tunguska Syneclise), Novosibirsk: Nauka, 1992, pp. 128–146.

Gubanov, A.P. and Yochelson, E.A., Wenlockian (Silurian) Gastropod Shell and Operculum from Siberia, *J. Paleontol.,* 1994, vol. 68, pp. 486–491.

Hallam, A., *Facies Interpretation and the Stratigraphic Record,* Oxford: Freeman and Company,1980. Translated under the title *Interpretatsiya fatsii i stratigraficheskaya posledovatel'nost',* Moscow: Mir, 1983.

Isakar, M.A., Mironova, M.G., and Saladzhyus, V.Yu., Mollusks of the Gasropoda Class, in *Atlas mollyuskov verkhnego ordovika i silura severo-zapada Vostochno-Evropeiskoi platformy* (Guide Book to Late Ordovician–Silurian Mollusks from the Northwestern East European Platform), Leningrad: Leningrad. Gos. Univ., 1990, pp. 5–15.

Jeppsson, L., An Oceanic Model for Lithological and Faunal Changes Tested on the Silurian Record, *J. Geol. Soc. London,* 1990, vol. 147, pp. 663–674.

Johnson, M., Baarli, B., Nestor, H., *et al.,* Eustatic Sea-Level Patterns from the Lower Silurian (Llandovery Series) of Southern Norway and Estonia, *Bull. Geol. Soc. Am.,* 1991, vol. 103, pp. 315–335.

Kyrts, A.L., Myannil, R.M., Pylma, L.Ya., and Einasto, R.E., Stages and Environments of Accumulation of the Kukersite (Algal) Oraganic Remains in the Ordovician and Silurian of Estonia, in *Vazhneishie bioticheskie sobytiya v istorii Zemli* (Most Significant Biotic Events in the Earth History), Tallinn: Inst. Geol. Akad. Nauk Estonii, 1991, pp. 87–94.

Lindstrom, G., On the Silurian Gastropoda and Pteropoda of Gotland, *K. Svenska Vetenskaps Akad. Handl.,* 1889, vol. 19.

Longstaff, J., The Genus *Loxonema, Quart. J. Geol. Soc. London,* 1909, vol. 65, pp. 210–228.

McKerrow, W., Ordovician and Silurian Changes in Sea Level, *J. Geol. Soc. London,* 1979, vol. 136, pp. 137–145.

Melchin, M., Graptolite Extinction at the Llandovery-Wenlock Boundary, *Lethaia,* 1994, vol. 27, pp. 285–290.

Mironova, M.G., Mollusks of the Gastropoda Class, in *Atlas siluriiskikh mollyuskov Podolii* (Guide Book to Silurian Mollusks from Podolia), Leningrad: Leningrad. Gos. Univ., 1987, pp. 8–21.

Murchison, R., *The Silurian System,* London, 1839.

Peel, J.S. and Wanberg-Eriksson, K., Gastropods, in *Lower Wenlock Faunal and Floral Dynamics—Vatenfallet Section, Gotland,* Jaanusson, V., Laufeld, S., and Skoglund, R., Eds., *Sver. Geol. Unders., Ser. C 762,* Uppsala, 1979, pp. 105–108.

Peel, J.S., Systematics and Palaeontology of the Silurian Gastropods of the Arisaig Group, Nova Scotia, *Biol. Skr. Dansk Videnskabs. Selsk,* 1977, vol. 21.

Pitcher, B., The Upper Valentian Gastropod Fauna of Shropshire, *Ann. Mag. Nat. Hist., Ser. 11,* 1939, vol. 4, pp. 83–132.

Reed, F., British Ordovician and Silurian Bellerophontacea, in *Palaeontographica Society, London, 1920,* 1921.

Seslavinskii, K.B., *Kaledonskoe osadkonakoplenie i vulkanizm v istorii Zemli* (Caledonian Sedimentation and Volcanism in the Earth History), Moscow: Nedra, 1987.

Seslavinskii, K.B., Global Transgressions and Regressions of the Paleozoic, *Izv. Akad. Nauk SSSR, Ser. Geol.,* 1991, no. 1, pp. 71–79.

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Rb–Sr and K–Ar Isotope Datings of Blue Clays in the Baltic Region: Implications for Geology

V. I. Vinogradov

Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 109017 Russia

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In 1994 and 1995, two papers were published to describe the geochronological studies of the Lower Cambrian deposits, the so-called blue clays, of the Baltic region (Gorokhov *et al.*, 1994, 1995). Both studies were carried out by using the same objects in one laboratory, and almost simultaneously. Nonetheless, the authors offered mutually exclusive conclusions. In the paper of 1994, the authors state that "on the basis of the obtained data the boundary between the Cambrian and Precambrian can be set at the level of about 530 ± 10 Ma," whereas in the paper of 1995, the authors conclude that their numerous Rb–Sr and K–Ar dates for blue clays are geologically meaningless. Since this contradiction has an impact on the basic problems of isotopic datings, I shall try to analyze in detail the factual data from both papers and the approaches to their interpretation.

The blue clays are interesting because they represent important Vendian–Cambrian boundary beds (Mens and Pirrus, 1977). The attempts to evaluate the isotopic age of this boundary in the Baltic sections were numerous (Firsov *et al.*, 1971; Gorokhov *et al.*, 1982; Keller, 1985; Krasnobaev *et al.*, 1986). The samples studied by Gorokhov *et al.* (1994; 1995) were obtained from two quarries, Kunda and Loksa, in Estonia and from the Kostovo-13 Well near St. Petersburg. The quarries expose the Lontova Formation which belongs to the basal part of the Lower Cambrian. The well section includes the same Lontova Formation in its upper part, and the Vendian Redkino Formation below.

PECULIAR ASPECTS OF ISOTOPIC DATING OF CLAY ROCKS

The difficulties of dating clay rocks are associated with two circumstances. First, the clay rocks, with rare exceptions, are essentially clastogenic and, therefore, can preserve information on the age of rocks exposed in the provenance. Consequently, the obtained isotopic dates will be older than the time of sediment formation. Second, clastic rocks, primarily fine-grained, experience intensive epigenetic alterations which may cause the distortion of isotopic systems. In this case, the obtained isotopic age could be younger than the time of sediment formation.

Theoretically, the ideal instances of close correspondence of isotopic ages and sedimentation time are possible. There are two variants: the strontium isotope composition in clay particles was at the isotopic equilibrium with the sea water during sedimentation or the early diagenesis of sediments, and the mechanical averaging of clastic particles resulted in the averaging of strontium isotope composition in sediment at the time of its accumulation (Misuzaki, 1994). In the Rb–Sr geochronometry, this is tantamount to setting the isotopic clocks at zero in the whole-rock samples. In both cases, if the rock remained to be the closed system after formation, then its age can be determined. This kind of information is the most valuable, and numerous attempts have been made to obtain it.

In many papers, the authors tried to reveal the criteria of the rock suitability for dating and procedures of preliminary treatment (Clauer, 1979; Clauer, 1981; Bonhomme, 1982; Gorokhov and Semikhatov, 1984; Pasteels, 1985; Bonhomme, 1987; Clauer *et al.*, 1990; Clauer and Chaudhuri, 1992). For instance, clay rocks were disintegrated into different grain-size fractions preliminarily studied under the microscope and by X-ray technique. In order to avoid the effect of secondary processes on the Rb–Sr isotope system, the samples were initially treated with a weak solvent (ammonium acetate, 1N HCl, etc.) to remove strontium that is weakly fixed on the surface of the particles and in the interlayer spacings. As a rule, after this treatment, a less radiogenic Sr with a lower Rb/Sr ratio than that of the overall Sr in the samples, passes into the solvent. This technique offers an attractive possibility of isochron dating using one sample and plotting three points on an isochron diagram corresponding to the untreated sample, its leachate, and the residue. According to the mass balance, such points should lie on a straight line in the isochron coordinates and can be used for formal age calculations. The false reasoning of this approach is obvious. On the one hand, elutriation is used to extract accidental allogenic Sr from the system, on the other hand, this allogenic Sr is incorporated into age calcula-

tions. In fact, the gradual accumulation of data on these triplets showed that the age calculations gained by using them are, in most cases, devoid of any geological meaning (Clauer *et al.* 1990; Ohr *et al.*, 1991).

The isotope measurements on different grain-size fractions of rocks often yield different results. Normally, the age of finer fractions is less than the supposed stratigraphic age (Bonhomme, 1987; Willis *et al.*, 1988). In most cases, the correspondence or noncorrespondence of the isotopic age to the stratigraphic age is actually the only criterion of the "correctness" of the obtained dates. However, correctness should be understood not as the concordance between the stratigraphic and isotopic ages, but as the correspondence of the latter to a certain geological event. The isotopic age acquires real value only when its "correctness" can be based on the isotopic data themselves irrespective of the existing geological notions. The "rejuvenated" ages of clay rocks usually bear information about the postsedimentary, epigenetic rock transformations, which take place step by step, episodically, and these very events can be dated by isotope methods. Ohr *et al.* (1991) showed, for example, that in the depth interval of 2100–2400 m of the Miocene–Pleistocene sand–clay sequence in the Texas coast, there is a sudden transition of smectite into illite. If the illite content above this depth is less than 50%, below it exceeds 80%. Concurrently, there is a sharp change in the Sr isotope composition. The Rb–Sr isotopic age of the <0.1 μm clay fraction below the transition zone, which is confined to the Lower Eocene beds (≅50 Ma), was found to be 35 Ma. The smectite–illite transition is accelerated at temperatures about 80–100°C, and this event can be reliably dated by the K–Ar method, if the K–Ar system was not disturbed at the temperature level of about 180°C (Aronson and Elliot, 1994). There are many indications now that the K–Ar and Rb–Sr methods can be applied to clay rocks for dating stages of their epigenetic transformations (Bonhomme, 1987; Ohr *et al.*, 1991; Aronson and Elliot, 1994). It is, in fact, the situation to be primarily taken into account in age determinations of clays and clay minerals. In the majority of cases, apparently, the age of sedimentation and early sediment diagenesis cannot be determined at all by isotopic methods; the latest discussion of the problem was published by Semikhatov (1995).

CRITERIA OF ISOTOPIC AGE SIGNIFICANCE

The most important and significant is the very fact of obtaining a linear arrangement of data points in isochron coordinates, in particular, when this arrangement satisfies the isochron requirements, namely if a scatter of data points near the straight line does not exceed analytical errors. The condition of data points arrangement on the isochron is too strict to allow any accidental happenings. The only alternative to the age interpretation of this linear distribution of points is the mixing process. If two components of different ages with their isotopic ratios $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ are mixed in different proportions, then all these mixtures will be in the isochron coordinates on the straight line connecting the extreme points. Naturally, the inclination angle of this line has no age meaning. But if even one other independent component participates in mixing, then the line satisfying the isochron conception will not appear at all. Therefore, in the natural environment, which is multicomponent in its essence, the chance of obtaining samples, which would reflect the line of mixing in the isochron coordinates, is highly improbable. In any case, this chance is less than the possibility of obtaining age relations. Consequently, every time, when speculating on the mixing lines, it is necessary to prove their actual existence and not just conceal behind them the inconvenient, for some reasons, age parameters of the linear arrangement of data points in the isochron coordinates.

The isochron, in fact, is also the mixing line but reflecting the mixing of samples of the same age. Its analogue in the K–Ar geochronometry is a series of concordant age values for different samples. In this case, the zero content of radiogenic Ar in the sample with zero K content will be an analog to the initial strontium isotope ratio. Unfortunately, this parameter cannot be determined from the data published in works in which I am interested (Gorokhov *et al.*, 1994; 1995), and my interpretation of these data is based only on coinciding age values, which in fact represent the criterion of validity of the age determination.

Finally, the important criterion, which testifies to the geological significance of the calculated age values, is the coincidence of results obtained by different (Rb–Sr and K–Ar) geochronometers.

DISCUSSION OF ANALYTICAL DATA

In the discussion presented below I use data published in two papers by Gorokhov *et al.* (1994; 1995).

The rubidium–strontium data. The isochron diagram (Fig. 1) shows the position of data points corresponding to the coarse-grained fractions of clays: six points to the fraction of >0.6 μm and three points to that of 0.4–0.6 μm. All samples were obtained from the quarries of the Lontova Formation. It is apparent, that the points are chaotically scattered, and their linear interpolation makes no sense. This scattering means that the isotope system in the coarse fraction of clays was out of equilibrium (or reequilibrated), and no definite notions about their age can be derived from these data. We can only suppose that among the analyzed samples there were no rocks older than 670 Ma. This age corresponds to the slope of the tentative dotted line connecting the extreme points in the Rb–Sr evolution diagram (Fig. 1). This approach, to be sure, is artificial and, of course, the indicated age is far from being absolute. This speculation, however, brings us to the principally important conclusion that the rocks of the Baltic

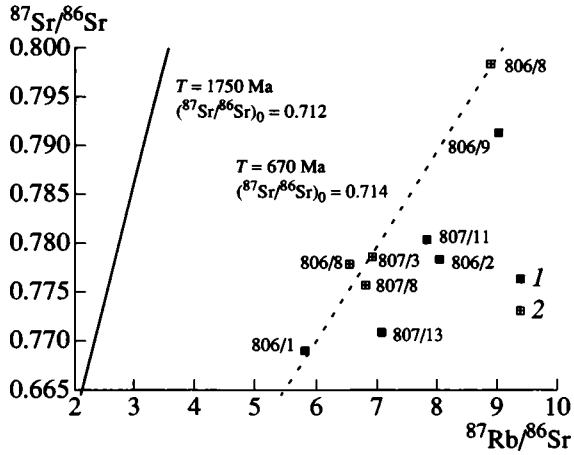

Fig. 1. Isochron diagram for the coarse fraction of blue clays: (*1*) fraction >0.6 μm; (*2*) fraction 0.4–0.6 μm. The number of points and their coordinates are from Gorokhov *et al.* (1994; 1995). A significant scatter of points do not allow their approximation by a single straight line. The slope of the conventional dotted line corresponds to the probable upper age limit. The solid conventional line shows the assumed position of the isochron corresponding to the average age of rocks of the supposed provenance. It is obvious that the isotopic information about the source rocks is completely deleted.

shield were the most plausible and perhaps the only possible source of the material for the Vendian–Cambrian sand–clay deposits in the northwest of the Russian platform. The average age of these rocks, estimated according to the occurrence frequency of isotopic dates in the Kola Peninsula, is 1750 ± 150 Ma (Pushkarev *et al.*, 1978). On the left-hand side of Fig. 1, the probable position of the 1750 Ma line corresponding to the acceptable initial Sr isotope ratio of 0.712 is shown. It is apparent that data points on the diagram do not show any indications of such an old age. This means that even the coarse clay fractions (up to 2 μm) experienced changes that erased the isotopic information about the provenance rocks. The changes, however, were not intense enough to reequilibrate the Rb–Sr system in the coarse clay fraction, or the equilibrium was again disrupted by recurrent events.

The situation with the finer fractions is different (Fig. 2). The table demonstrates the results of my recalculations of data that were presented in Gorokhov *et al.* (1994; 1995). The analytical errors reported and used in calculations were ±2% and ±0.1% for $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios, respectively. The calculations were carried out by the method of York (1966) preventing subjective interpretations of the points' dispersion. All the linear relations, apart from the doublepoint line 3, satisfy the isochron parameters controlled by using the χ-square criterion (Sokolov and Buyakaite, 1986). Since the rocks studied by Gorokhov *et al.* have experienced epigenetic changes, I considered only those samples that previously were not treated by ammonium acetate.

Several results are of interest. First, ages obtained for different grain-size fractions turn out to be nearly identical. More significant differences are in the initial isotope ratios. Though they formally can be considered similar within the accepted error limits, the differences are too great for attributing data points of different fractions to one straight line holding the isochron parameters.

The integration of samples of the Lontova and Redkino formations from well Kostovo-13 to plot one isochron can be considered objectionable. In Fig. 2, the points on the isochron diagram are shown to include two points for the grain fraction <0.2 μm from the Estonian quarries. The dotted lines on the diagram approximate every group of points. The lower line is drawn on the basis of five samples of the Redkino Formation, the middle line approximates ten samples of the Lontova Formation recovered from the well, and the upper line connects two points of the Lontova Formation samples from the quarries. In both groups of data points for samples from well Kostovo-13, the scatter relative to approximating straight lines is quite great, and calculated ages have great errors: 455 ± 117 and 472 ± 159 Ma. The integration of both groups into one (the solid line in Fig. 2) essentially improves the parameters of linear dependence, and respective age is 539 ± 53 Ma. This age seems to correspond better to the real geological event.

The Rb–Sr isochrons are thus obtained for different fine-grained fractions of blue clays on the basis of many samples separated by considerable distances and collected from different stratigraphic levels. These isochrons have nearly identical ages of about 540 ± 40 Ma and initial strontium isotope ratios varying from 0.707 to 0.719 ± 5. The question is whether these isochrons can be regarded as the mixing lines, as it was suggested (Gorokhov *et al.*, 1995).

Figure 3 shows the position of isochrons and their end points. If we consider them as mixing lines, then we must detect the components that were mixed. We can take for the end components of mixing those fractions, for instance, which have Rb–Sr characteristics of the extreme right upper and left lower points of the line in Fig. 3. These points correspond to samples 807/8 (grain-size fraction of 0.1–0.4 μm) and 806/8 (0.2–0.3 μm) (Gorokhov *et al.*, 1994, Table 3; Gorokhov *et al.*, 1995, Table 3). Connecting these two points, we obtain the initial strontium isotope ratio of 0.703 that is absolutely unreal. Selecting any point corresponding to the coarse fraction as a possible end member of the mixing line, we only aggravate the situation. When any other component, which is located on the actually obtained lines or on their extensions, is selected, the result is a mere violation of the isochron dependence.

Consequently, it is necessary to figure out the final mixing components in order to state that the straight

line on the Rb–Sr evolution diagram can be regarded as depicting the mixing process. I believe that this cannot be done with the material at hand, and that the obtained straight lines should be regarded as real isochrons. These isochrons correspond to an event that occurred 540 ± 40 Ma ago, caused the rock transformation and reset the isotopic chronometer at zero.

The potassium–argon data. The results of K–Ar determinations (Gorokhov *et al.*, 1994; 1995) are summarized in Fig. 4. As the authors of these papers point out, there is a general tendency of the measured age increase with the growth of the clay fraction size. This is an ordinary phenomenon typical of fine-grained sedimentary rocks when they experience epigenetic changes. The K–Ar systems of fine fractions can be more easily disturbed, and their isotopic ages either characterize the terminal influence of an active factor, or represent a later and weaker (the last) stage of changes in the rock composition. Coarser fractions are more resistant to the epigenetic processes, and the age of these fractions indicates the time of a stronger event that influenced the rock. Recently, a special detailed study of these processes was carried out by using the Middle Cambrian graywacke from the northwestern part of Morocco (Clauer *et al.*, 1995). The results showed that different grain-size fractions of these sediments retained evidence on three stages of their transformation occurred 205, 305 and 445 Ma ago. Each of these stages corresponds to a period of thermal activization in that territory.

As it is evident from Fig. 4, the K–Ar data, obtained by Gorokhov and his colleagues, are also rather clearly divisible into three groups. The scatter in each group of age values is within the analytical error, whereas between the groups it is greater. The group of youngest ages (488 ± 9 Ma) is probably corresponding to the last stage of rock transformations. According to the authors of the cited papers, the young age (estimated to be 470–480 Ma) is related "... to ascending movements when the rocks were incorporated into the zone of circulation of meteoric waters" (Gorokhov *et al.*, 1995, p. 61). More ancient dates (517 and 545 Ma) can hardly be correlated with any particular event, but they may have a certain geological implication. This seems to be particularly feasible for the value of 545 Ma almost exactly coinciding with the age values obtained by the Rb–Sr method (see table).

CONCLUSION

The data discussed above led me to positive conclusions. First, it is definitely proved that the Vendian–Cambrian deposits in the northwestern part of the Russian platform experienced several stages of transformation. At least two of them, 490 and 540 Ma in age, are definitely dated by the K–Ar and Rb–Sr methods. I can in no way agree with the authors of the papers discussed that their dates are meaningless. The more ancient date substantiated by both methods of isotope

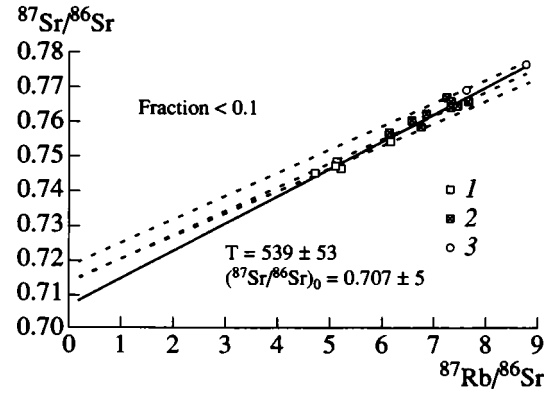

Fig. 2. Isochron diagram for the fine fraction (<0.1 μm) of blue clays: (*1*) samples of the Redkino Group; (*2*) Samples of the Lontova Group from Well Kostovo-13; (*3*) samples of the Lontova Group from the quarries. The dotted lines approximate each of the three series of samples. The solid line approximates all samples from the well.

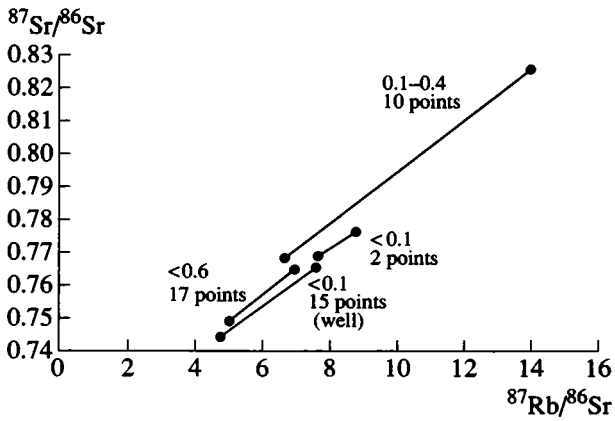

Fig. 3. Isochrons for different fractions (table). The figure shows that it is impossible to interpret these isochrons as mixing lines.

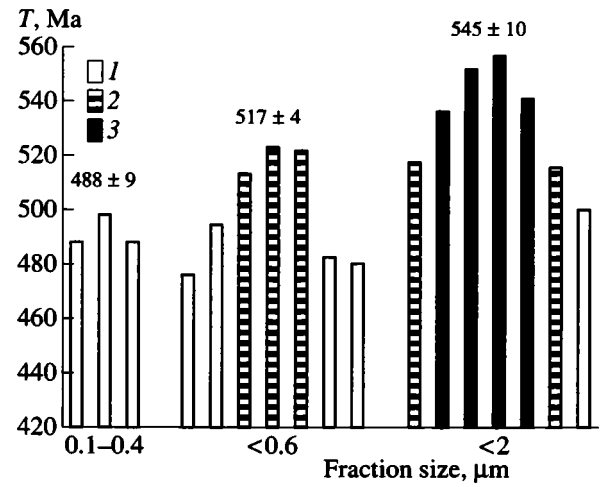

Fig. 4. Histogram of the K–Ar ages measured in different grain-size fractions. Three groups of K–Ar age determinations with the average values of (*1*) 488 ± 9, (*2*) 517 ± 4, and (*3*) 545 ± 10 Ma.

Results of calculating the isochron relations in fine clay fractions

Number of series	Fraction size, μm	Number of points	Age, Ma	$(^{87}Sr/^{86}Sr)_0$	MSWD
1	<0.6*	17	547 ± 47	0.710 + 4	0.32
2	0.1–0.4**	10	528 ± 42	0.719 ± 6	1.62
3	<0.1*	2	465	0.718	
4	<0.1***	15	539 ± 53	0.707 ± 5	1.34

* Samples from quarries;

** Calculation includes all fractions of this size interval;

*** Samples from the well.

dating is of particular importance. This date indicates that 540 ± 40 Ma ago the Vendian–Cambrian deposits experienced a stage of epigenetic transformation. Consequently, the accumulation of the Lontova series occurred at an earlier time. Unfortunately, the time of sedimentation, or the time of the early diagenesis of the Lontova sediments cannot be established by the analysis of the sediments themselves, however there is no reason for the pessimistic conclusions of the authors of the cited papers. At the same time, their excessively optimistic view concerning the possibility of reliable dating the sediment formation time by studying different fractions of clay minerals seems to be unjustified. It appears that the Rb–Sr and K–Ar systems of the fine-grain sediments are not isolated in the mineral grains proper. Therefore, the more reliable data about the reequilibrated isotopic systems and the age of the last stage of this event can be obtained by analyzing the whole-rock samples.

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REFERENCES

Aronson, J.L. and Elliot, C., Illite/Smectite, a Valuable K-Ar Clock for the Secondary History of the Sedimentary Basin, in *Abstracts of ICOG. US Geol. Surv. Circular 1107,* 1994, p. 13.

Bonhomme, M.G., The Use of Rb-Sr and K-Ar Dating Methods As a Stratigraphic Tool Applied to Sedimentary Rocks and Minerals, *Precambrian Res.*, 1982, vol. 18, no. 1/2, pp. 5–25.

Bonhomme, M.G., Type of Sampling and Comparison between K-Ar and Rb-Sr Isotopic Dating of Fint Fractions from Sediments in an Attempt to Date Young Diagenetic Events, *Chem. Geol. (Isot. Geosci. Sect.),* 1987, vol. 65, no. 3/4, pp. 209–222.

Clauer, N., Rb-Sr and K-Ar Dating of Precambrian Clays and Glauconites, *Precambrian Res.*, 1981, vol. 15, no. 3, pp. 331–352.

Clauer, N., A New Approach to Rb-Sr Dating of Sedimentary Rocks, in *Lectures in Isotope Geology,* Berlin: Springer, 1979, pp. 30–51.

Clauer, N. and Chaudhuri, S., Isotopic Signatures and Sedimentary Records, *Lecture Notes in Earth Sci.*, 1992, vol. 43.

Clauer, N., O'Neil, J.R., Bonnot-Courtois, C., and Holtzaffel, T., Morphological, Chemical and Isotopic Evidence for Smectite in Marine Sediments, *Clays Clay Miner.*, 1990, vol. 38, no. 1, pp. 33–36.

Clauer, N., Rais, N., Schaltegger, U., and Picue, A., K-Ar Systematics of Clay-to-Mica Minerals in a Multi-Stage Low-Grade Metamorphic Evolution, *Chem. Geol. (Isot. Geosc. Sec.),* 1995, no. 2, pp. 305–316.

Firsov, L.V., Nikolaeva, I.V., Lebedev, Yu.N., and Solntseva, S.N., Composition, Origin, and Absolute Age of Mica Minerals from the Lower Cambrian Blue Clay of the Baltic Region, in *Glaukonit v sovremennykh nizhnepaleozoiskikh i dokembriiskikh otlozheniyakh* (Glauconite from Recent, Lower Paleozoic, and Precambrian Deposits), Moscow: Nauka, 1971, pp. 165–192.

Gorokhov, I.M. and Semikhatov, M.A., Behavior of Rb and Sr during the Sedimentary Rock Formation, *Litol. Polezn. Iskop.*, 1984, no. 2, pp. 87–109.

Gorokhov, I.M., Clauer, N., Kutyavin, E.P., *et al.*, Rubidium–Strontium Systems in the Vendian–Cambrian Deposits of the Northwestern East European Platform, in *Problemy izotopnogo datirovaniya protsessov vulkanizma i osadkoobrazovaniya* (Problems of Isotopic Dating of Volcanic and Sedimentary Processes), Kiev: Naukova Dumka, 1982, pp. 38–39.

Gorokov, I.M., Clauer, N., Turchenko, N.N., *et al.*, Rb-Sr Systematics of Vendian-Cambrian Claystones from the East European Platform: Implications for a Multi-Stage Illite Evolution, *Chem. Geol. (Isot. Geosci. Sect.),* 1994, vol. 112, no. 1/2, pp. 71–89.

Gorokhov, I.M., Kutyavin, E.P., Mel'nikov, N.N., and Turchenko, T.L., Isotopic Datings of the Lower Cambrian Clays from Estonia and their Interpretation, *Stratigr. Geol. Korrelyatsiya,* 1995, vol. 3, no. 5, pp. 54–65.

Keller, B.M., Geochronology of the Vendian in the USSR, in *Vendskaya sistema* (Vendian System), Moscow: Nauka, 1985, vol. 2, pp. 161–167.

Krasnobaev, A.A., Ronkin, Yu.L., and Lepikhina, O.P., The Rubidium–Strontium Dating of Clay Sediments, *Izv. Akad. Nauk SSSR, Ser. Geol.*, 1986, no. 6, pp. 3–17.

Mens, K. and Pirrus, E., *Stratotipicheskie razrezy kembriya Estonii* (Cambrian Stratotype Sections in Estonia), Tallinn: Valgus, 1997.

Misuzaki, A.M.P., Cordani, U.G., Kovashita, K., and Thomaz-Filho, A., Rb-Sr Systematics in Recent Sediments and Its Bearing for Geochronological Interpretations, in *Abstracts of ICOG-8. US Geol. Survey Circular 1107,* 1994, p. 220.

Ohr, M., Halliday, A.N., and Peacor, D.R., Sr and Nd Isotopic Evidence for Punctuated Clay Diagenesis, Texas Gulf Coast, *Earth Planet. Sci. Lett.*, 1991, vol. 105, no. 1, pp. 110–126.

Pasteels, P., Radiometric Datation of Sediments, *Rend. Soc. Ital. Mineralog. Petrolog.*, 1985, vol. 40, no. 1, pp. 17–24.

Pushkarev, Yu.D., Kravchenko, E.V., and Shestakov, G.I., *Geokhronologicheskie repery dokembriya Kol'skogo poluos-*

trova (Geochronological Reference Points for the Precambrian of the Kola Peninsula), Leningrad: Nauka, 1978.

Semikhatov, M.A., Methodic Principles of the Riphean Stratigraphy, *Stratigr. Geol. Korrelyatsiya,* 1995, vol. 3, no. 6, pp. 33–50.

Sokolov, D.D. and Buyakaite, M.I., Some Aspects of the Least-Squares Method Application in the Rubidium–Strontium Geochronometry, in *Evolyutsiya sistemy kora–mantiya* (Evolution of the Crust–Mantle System), Moscow: Nauka, 1986, pp. 207–217.

Willis, K.M., Stern, R.J., and Clauer, N., Age and Geochemistry of Late Precambrian Sediments of the Hammat Series Form the Northeastern Desert of Egypt, *Precambrian Res.*, 1988, vol. 42, no. 1–2, pp. 173–187.

York, D., Least-Squares Fitting of a Straight Line, *Can. J. Phys.,* 1996, vol. 44, pp. 1079–1086.

Stratigraphy and Geological Correlation, Vol. 5, No. 6, 1997, pp. 626–630. Translated from Stratigrafiya. Geologicheskaya Korrelyatsiya, Vol. 5, No. 6, 1997, pp. 107–112.
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Two Different Approaches to the Use of the Isochron Method for Dating Sedimentary Rocks[1]

I. M. Gorokhov and N. N. Mel'nikov

Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, nab. Makarova 2, St. Petersburg, 199034 Russia

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Someone will misinterpret you, even though your explanation is so clear that any false interpretation is impossible.

Arthur Blogh. Consequence of the third Cheeseholm's law.

Key words: *isotope geochronology, clays, dating.*

INTRODUCTION

We are grateful to the Editorial Board of this journal for letting us read a paper by Vinogradov (1997) who used the results of our recently published studies. In his paper he elaborated ideas that are of fundamental importance in isotope geochronology, and he found our results suitable for their illustration but vulnerable for criticism. In this paper we intend to prove that a considerable number of Vinogradov's comments proceeded from his insufficient knowledge of the problems discussed in general and of the subject matter of our papers in particular. Moreover, some of his statements contradict the modern principles of geochronology, and the way he illustrates them using our results does not stand up.

For the convenience of the subsequent presentation, we will remind the contents and objectives of our papers discussed by Vinogradov. For brevity we will refer to the paper published in *Chemical Geology* (Gorokhov *et al.*, 1994a) as paper I, and to the paper published in *Stratigraphy, Geological Correlation* (Gorokhov *et al.*, 1995) as paper II.

The objective of paper I was to offer a new approach to the dating of those stages in the geologic history of clays that were related to particular mineral transformations. This approach incorporates the separation, from one or several samples, of a number of clay fractions of different and narrow size ranges of mineral particles and their subsequent X-ray, electron microscopic, and isotopic studies. The aim of this approach is to enrich and identify minerals that carry isotopic geochronological information. For instance, using clays of the Early Cambrian age from the Lontova Horizon, we managed to separate and analyze three illite generations of different ages and with different morphological, crystal chemical, and rubidium–strontium characteristics. Accordingly, we obtained information on three stages in the geological history of the sedimentary material: the minimum age of the source area, the age of burial diagenesis, and the time of retrogressive catagenesis.

In paper II we pursued an absolutely different goal. We intended to show that the popular approach to dating clay sediments that is based on the separation of small-size particle fractions, the particle size of which is bounded by the upper limit alone (for example, smaller than 1 μm) or varies over a fairly great range, does not provide information on the ages of mineral transformations and may lead to meaningless isotope (including isochron) dates, because these size fractions are not monogenetic but usually consist of two or more clay mineral generations of different ages.

IN RESPONSE TO THE CRITICAL COMMENTS

To begin with, a significant amount of Vinogradov's criticism of our papers is groundless.

(1) Explaining the cause that motivated him to criticize our papers, Vinogradov writes that our papers I and II offer *mutually exclusive* (hereinafter italics ours) conclusions. He also mentions that authors state in the paper of 1994 that they established the minimum age of 533 ± 8 Ma for the Lower Cambrian pre-trilobite deposits, whereas in the paper of 1995 our statement was that numerous Rb–Sr and K–Ar dates are meaningless. Both of these statements are open to argument in his opinion.

It is obvious to any unprejudiced reader that paper I contains an approach and technique *recommended* for use in dating clays by the Rb–Sr method. This paper demonstrates which dates are meaningful and why. It is equally obvious that paper II illustrates, on the contrary, how isotopic geochronological studies should not be

[1] Comments on paper by V. I. Vinogradov "Rb–Sr and K–Ar Dating of Blue Clays in the Baltic Region: Implications for Geology."

done, and provides numerous examples of meaningless dates. The conclusions of our two papers, therefore, are in no way mutually exclusive but complement one another.

(2) One other critical comment is that our technique of using triplet leaching is not suitable for the isotopic dating of clay minerals. Summarizing various approaches to the dating of clay sediments known from the literature, Vinogradov writes:

> *To avoid the effects of secondary processes on the Rb–Sr isotope system*, samples are first treated using a weak solvent (ammonium acetate, 1N HCl, etc.) to remove strontium that is weakly fixed on the surface of the particles... This technique offers an attractive possibility of isochron dating using one sample and plotting three points on an isochron diagram: an untreated sample, its leachate, and the residue... The false reasoning of this approach is obvious. *On the one hand, the leaching procedure is used to remove accidental allogenic strontium from the system, on the other hand this allogenic strontium is incorporated into age calculation*
>
> (Vinogradov, 1997, p. 620).

The author is wrong thinking that the purpose of leaching is to remove strontium from the system. In fact, leaching is performed because the leachate usually contains information about the mineral deposition environment (Clauer, 1982; Clauer *et al.*, 1982, 1984, 1990). The nature of strontium that is poorly incorporated into the structure of clay particles and found in the leachate, can be a matter of debate (Gorokhov, 1985). Naturally, it cannot be ruled out that strontium might find its way into the system after illite formation; this problem must be solved individually in each particular case. In Paper I we provide enough arguments to support the fact that the matter we leached from different size fractions of clay minerals was, at the instant of illite formation, in the isotopic equilibrium with the illite structure, and that the Rb–Sr system of these size fractions remained closed. If there are grounds to believe that the material of the leachate and that of the residue were cogenetic and contemporaneous, our method of dating cannot provoke objections. The references provided by Vinogradov to support his thesis "that most of the ages calculated from them (from triplets) are meaningless" consists of two papers and does not look convincing, especially in view of the fact that nothing of the sort was stated by the authors of one of them (Clauer *et al.*, 1990); these authors believed triplet-based ages to be meaningless not because of the absence of equilibrium between the leachate and the residue, but because of the mixed character of the illite size fractions studied.

(3) Much attention in Vinogradov's paper is given to the problem that components of different ages can be mixed, the issue to which Faure (1986) devoted as much as a whole chapter in his book where he systematized the world's experience in isotopic geochronology. We must admit with regret that there is no use in disputing this issue. Our opponent seems far from being an expert in this field, probably because of his conviction that this problem is of little significance to Rb–Sr geochronology in general. This resulted in the occurrence of a number of outspoken blunders in his paper. For instance, trying to find mixed components in our samples, he searched for two components instead of eight, as required by the theory, in order to produce four mixing lines. Another example concerns his geochemical constructions on the basis of our data. Suffice it to mention his extrapolation of mixing lines beyond the data points corresponding to the end members of the mixture. It was probably for the same reason that Vinogradov was not willing to notice numerous *isotopic* and *nonisotopic* evidence provided in our papers in support of the mixed nature of the Lontova clays.

(4) Finally, Vinogradov believes that in most cases the age of sedimentation or of the early diagenesis of sediments probably cannot be determined at all using the clay sediments themselves. As regards the age of sedimentation, he is absolutely right, and this has been recognized in many publications (Gorokhov, 1985; Faure, 1986; to name but a few). The question concerning the age of early diagenesis is not that clear. First of all, there is a problem of terminology: the meaning of the term "early diagenesis" is understood differently by Russian and foreign investigators. Without going into the discussion of this issue, it should be noted that when (and only when!) combined with the mineralogical and crystal chemical studies of geochronometers, the isotope methods are able to date fairly reliably the stages of the formation or transformation of clay minerals (Clauer, 1982, 1995; Glasmann *et al.*, 1989; Burley and Flisch, 1989; Schaltegger *et al.*, 1994; Ohr *et al.*, 1994; Gorokhov *et al.*, 1994a, b; Toulkeridis and Clauer, 1995; Clauer and Chaudhuri, 1995). Moreover, dates for sedimentary, in particular, clay rocks are in principle not different from dates for magmatic or metamorphic rocks: all of them date the late instant, the timing of a respective isotopic system closure, rather than the timing of some other geologic process. The question of how close this timing is to the dated event can be answered after close examination in each particular case.

CRITERIA OF ISOTOPIC AGE SIGNIFICANCE

The discussion of this section in Vinogradov's (1997) paper calls for some introduction. The modern practice of isotopic isochron dating in geology includes, in addition to the problem formulation (dating of rocks or a process), the following logical steps: (1) the choice of a material that is likely to bear age information; (2) the choice and study of the physical, chemical, mineralogical, or other properties of the chosen material for the purpose of establishing its suitability for solving the problem at hand: (3) the isotopic

analysis of the material and the calculation of analytical data statistics; and (4) the interpretation of the geological significance of the latter. This is necessary because a line in an isochron diagram can be taken as an isochron only if it satisfies the following conditions: (1) the rock samples, on the basis of which it has been plotted, are isochronous, (2) the environment, in which the rock samples originated, was in isotopic equilibrium, (3) the isotopic systems remained closed after their formation, and (4) there is no scatter in the data points in excess of that attributable to analytical uncertainty. None of the isotopic systems offers an intrinsic measure for checking the fulfillment of these conditions. For this reason the suitability of an isochron model for each particular set of samples has to be verified using independent methods.

Nevertheless, Vinogradov has found this intrinsic measure. He writes:

> The most important and significant is the very fact of obtaining a linear arrangement of data points in the isochron coordinates, in particular, when this arrangement satisfies the isochron requirements, namely, if a scatter in the data points near the straight line does not exceed analytical errors. The condition of data point arrangement on the isochron is too strict to allow any accidental happenings
>
> (Vinogradov, 1997, p. 621).

It appears that Vinogradov has formulated an absolutely new measure of consistency between analyzed samples and an isochron model. In fact, he claims that no geochemical or any other nonisotopic prerequisites are needed to plot an isochron. In other words, the fulfilment of conditions, such as the same age, equilibrium, and system closure are not necessary or sufficient for the linear data point arrangement in an isochron plot, but a linear data point arrangement alone is sufficient for taking the parameters of this line (age and an initial $^{87}Sr/^{86}Sr$ ratio) to be meaningful in a geological aspect. So a verifying condition is transformed into a determining one.

Although the criterion formulated by Vinogradov looks stunning, one cannot but admit that if it were valid it would make the work of geochronologists easier and save money. Unfortunately, as we will show below, his formulation of the new criterion and arguments in its support are groundless.

His only argument in support of this measure is the strictness of statistical requirements imposed on isochrons, which must render any accidental arrangement of analytical data on the line highly improbable. However, even approximate estimates of this high improbability are not given, neither is it mentioned for which minimum number of data points this measure is valid. Nothing is said about the fact that the extent of this strictness is wholly dependent on the values of analytical errors used in the calculation. The importance of this fact can be exemplified by Vinogradov's calculation based on the data reported in our papers I and II. He took the resulting relationships to be isochronous on the basis of small MSWD values. However he was wrong when using our errors for $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ values, which were quoted in our papers at 2σ level (as was indicated in the texts), whereas in this case he should have used half as small values. As a result, even in a purely mathematical context, he took lines where a scatter in the data points exceeded the analytical error to be isochrons, which are not isochrons even in his own understanding.

The deplorable results of the practical application of the new measure are obvious in Vinogradov's paper, where he grouped our analytical data at will (e.g., he combined samples from different stratigraphic levels into one data set) and plotted a considerable number of diagrams presenting them as isochron diagrams. He did this ignoring all mineralogical and genetic evidence for the samples available in our papers, except for the positions of their data points on the $^{87}Rb/^{86}Sr$–$^{87}Sr/^{86}Sr$ diagrams. Referring to the fact that the analyzed rocks had experienced epigenetic alteration, he included in his calculations only those samples that had not been treated with ammonium acetate. However, while selecting samples for plotting diagrams, he overlooked the fact that as much as 52 % of strontium in the samples represented the leached component (Table 3 in paper I), the isotopic composition of which was considerably different from that of the clay mineral proper (that remained in the residue) and, moreover, varied from one size fraction to another. For this reason the use of an isochron model in processing the data obtained for the size fractions that had not been treated with ammonium acetate was absolutely incorrect, especially when admitting that Vinogradov's thesis about the allogenic nature of leached strontium is correct.

It is obvious, therefore, that in this first demonstration of the new measure offered by Vinogradov for plotting meaningful isochrons, he managed to combine, on his "isochron" data that were known to be unsuitable for this purpose. It is not difficult to foresee the deplorable results of using this approach: the amount of Rb–Sr analytical data reported in the geochronological literature is great enough for Vinogradov's followers, if there are any, to group them into data sets which will satisfy the statistical requirements of the isochron relationship, and therefore will yield any conceivable ages and isotopic–geochemical parameters of origination environments. This will undoubtedly discredit isotopic geochronology in general and its isochron methods in particular.

In the context of the above considerations, we need not go into the discussion of Vinogradov's interpretation of our Rb–Sr data. There are two points, however, that deserve consideration.

(1) The sole referral of our opponent to geological information in Fig. 1 (Vinogradov, 1997) need be clarified. The author states that the most realistic, and prob-

ably the only likely source of siliciclastic material for the accumulation of Vendian–Cambrian arenaceous and shaly sediments in the northwestern Russian Platform were the rocks of the Baltic Shield with an average age of 1750 ± 50 Ma. It is pertinent to refer, in this context, to Mens (1980) and Pirrus (1980), who proved another source of the Lontova deposits in the Baltic region—Riphean rocks from the internal areas of the East-European Platform.

(2) The opponent's operations with data points and plotting a resulting isochron through them with an age of 539 ± 53 Ma (Fig. 2 in Vinogradov, 1997) appear to be (probably unexpectedly for the author) a classical manner of plotting a pseudo-isochron relationship (p. 135 and Figs. 7, 12b in Gorokhov, 1985).

As regards the opponent's interpretation of the K–Ar data reported in paper II and based on the mixtures of illites known to be of different ages, his method is no different from the disparaging habit of some users of dating results to choose those isotopic dates that fit their geological models, disregarding the source material on the basis of which the dates were obtained, the method of dating, and the substantiation of the geochronological interpretation.

WHO DETERMINED THE MEANINGFUL AGE OF BLUE CLAYS IN THE BALTIC REGION?

In the concluding section of his paper, Vinogradov states that he positively proved the occurrence of several alteration stages of the Vendian–Cambrian rocks in the Baltic region. "At least two of them, 490 and 540 Ma in age, are definitely dated by the K–Ar and Rb–Sr methods. I can in no way agree with the authors of the papers *discussed* (papers I and II. I. G and N. M.) that their dates are meaningless" (Vinogradov, 1997, p. 623).

As has been mentioned above, his "positive proofs" are based on his improper use of an isochron model for interpreting our Rb–Sr data, for which the conditions of the model do not hold. The use of selected values from the total set of the mixed K–Ar dates does not make these proofs more convincing. Furthermore, by referring to *both* of our papers he misleads the readers who have not read the earlier of them. This is its summary (pp. 85–86 in Gorokhov *et al.*, 1994a):

> *The subsidence of the Lontova sediments was accompanied by the crystallization of second-generation 1M illite 533 ± 8 Ma ago. This illite was formed from the detrital material of first-generation 2M illite, which is 722 ± 13 Ma old. In the Ordovician–Early Silurian time, extensive open-system ground water circulation took place, and the previously formed illite was partially recrystallized and transformed into the new low-temperature 1M–1Md illite of the third generation 430–480 Ma ago.*

We believe that no comments are needed here.

CONCLUSION

The use of our papers (I and II) by Vinogradov as an illustration of his new ideas in geochronology was an unfortunate choice. Nevertheless, his contribution to the theory of Rb–Sr geochronology is unquestionable: he added one more, very bright and original method of obtaining meaningless isotope dates to the list of techniques we demonstrated in paper II.

This result, however, was not the only reason for this dispute. What is important is the sharp definition of a crucial difference between two approaches to isotopic geochronological studies in general and to the dating of sedimentary rocks in particular, the latter being among the most difficult objects of study. We believe that the interpretation of isotopic geochronological data, which mark particular geologic events, is impossible without a thorough study of mineral matter containing geochronological information and its transformation under the impact of these events. As follows from the current literature, it was the comprehensive study of geochronometers and the secondary alteration histories of the rocks enclosing them that contributed much to recent improvements in the methods of dating magmatic, metamorphic, and sedimentary rocks. In Vinogradov's opinion, however, the acquisition of analytical data and their subsequent processing in terms of the isochron model systematics are self-sufficient procedures in isotopic geochronological investigations.

An attempt to replace the study of the rocks to be dated by the mathematical processing of analytical data returns us to the past. The creation of isochron models in the 1950–1960s, combined with the introduction of the progressive methods of statistical data processing, was undoubtedly a leap forward which promoted a rapid advance of isotope geochronology. Even though in those times there might be investigators who believed the new tools to be powerful enough to solve any problems, none of them excluded the examination of material to be dated. It is especially strange that a publication of this kind appeared now, after more than thirty years of developments in the theory and practice of isochron dating.

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REFERENCES

Burley, S.D. and Flisch, M., K-Ar Geochronology and the Timing of Detrital I/S Clay Illitization and Authigenic Illite Precipitation in the Piper and Tartan Fields, Outer Moray Firth, UK North Sea, *Clay Miner.*, 1989, vol. 24, no. 2, pp. 285–315.

Clauer, N., The Rubidium-Strontium Method Applied to Sediment: Certitudes and Uncertainties, in *Numerical Dating in Stratigraphy*, Odin, G.S., Ed.,. Chichester: Wiley, 1982, pp. 245–276.

Clauer, N., Isotopic Constraints to the Concepts of Clay Genesis, in *Euroclay'95, Clays and Clay Materials Sciences,*

Leuven, Belgium, August 20–24, 1995. Book of Abstracts, Invited Lectures and Oral Presentations, 1995, pp. 19–20.

Clauer, N. and Chaudhuri, S., *Clays in Crustal Environments: Isotopic Dating and Tracing,* Berlin: Springer, 1995.

Clauer, N., Giblin, P., and Lucas, J., Sr and Ar Isotope Studies of Detrital Smectites Form the Atlantic Ocean (DSDP, Legs 43, 48 and 50), *Isotop. Geosci.*, 1984, vol. 2, no. 2, pp. 141–151.

Clauer, N., Hoffert, M., and Karpoff, A.-M., The Rb-Sr Isotope System as an Index of the Origin and Diagenetic Evolution of Southern Pacifc Red Clays, *Geochim. Cosmochim. Acta,* 1982, vol. 46, no. 12, pp. 2659–2664.

Clauer, N., O'Neil, J.R., Bonnot-Courtois, C., and Holtzapffel, T., Morphological, Chemical and Isotopic Evidence for an Early Diagenetic Evolution of Detrital Smectite in Marine Sediments, *Clays Clay Miner.,* 1990, vol. 38, no. 1, pp. 33–46.

Faure, G., *Principles of Isotope Geology,* New York: Wiley, 1986. Translated under the title *Osnovy isotopnoi geologii,* Moscow: Mir, 1989.

Glasmann, J.R., Larter, S., Briedis, N.A., and Lundegard, P.D., Shale Diagenesis in the Bergen High Area, North Sea, *Clays Clay Miner.*, 1989, vol. 37, no. 2, pp. 97–112.

Gorokhov, I.M., *Rubidii-strontsievyi metod izotopnoi geokhronologii* (The Rubidium–Strontium Method of Isotopic Geochronology), Moscow: Energoatomizdat, 1985.

Gorokhov, I.M., Clauer, N., Turchenko, T.L., *et al.*, Rb-Sr Systematics of Vendian-Cambrian Claystones from the East European Platform: Implications for a Multistage Illite Evolution, *Chem. Geol.*, 1994a, vol. 112, no. 1/2, pp. 71–89.

Gorokhov, I.M., Kutyavin, E.P., Mel'nikov, N.N., and Turchenko, T.L., Isotopic Datings of the Lower Cambrian Clays from Estonia and their Interpretation, *Stratigr. Geol. Korrelyatsiya,* 1995, vol. 3, no. 5, pp. 54–65.

Gorokhov, I.M., Turchenko, T.L., and Melnikov, N.N., Multi-Stage Illite Evolution in Upper Proterozoic Shales: Rb-Sr, XRD and TEM Studies, V.M. Goldschmidt Conference, Edinburgh, 1994, Extended Abstracts, *Miner. Mag.*, 1994b, vol. 58A, pp. 341–342.

Mens, K.A., Vendian–Cambrian Paleogeography of the Western part of the East European Platform, *Paleogeographiya i litologiya venda i kembriya zapada Vostochno-Evropeiskoi Platformy* (Vendian–Cambrian Paleogeography and Lithology in the West of the East European Platform), Keller, B.M. and Rozanov, A.Yu., Eds., Moscow: Nauka, 1980, pp. 26–29.

Ohr, M., Halliday, A.N., and Peacor, D.R., Mobility and Fractionation of Rare Earth Elements in Argillaceous Sediments: Implication for Dating, Diagenesis, and Low-Grade Metamorpphism, *Geochim. Cosmochim. Acta,* 1994, vol. 58, no. 1, pp. 289–312.

Pirrus, E.A., Problems of the Vendian–Cambrian Lithology in the Western Part of the East European Platform, *Paleogeographiya i litologiya venda i kembriya zapada Vostochno-Evropeiskoi Platformy* (Vendian–Cambrian Paleogeography and Lithology in the West of the East European Platform), Keller, B.M. and Rozanov, A.Yu., Eds., Moscow: Nauka, 1980, pp. 97–104.

Schaltegger, U., Stille, P., Rais, N., Piqué, A., and Clauer, N., Neodymium and Strontium Isotopic Dating of Diagenesis and Low-Grade Metamorphism of Argillaceous Sediments, *Geochim. Cosmochim. Acta,* 1994, vol. 58, no. 5, pp. 1471–1481.

Toulkeridis, T. and Clauer, N., Isotopic Dating of Proterozoic-to-Archean Clay Minerals: an Assesment, in *Euroclay'95, Clays and Clay Materials Sciences, Leuven, Belgium, August 20–24, 1995. Book of Abstracts, Posters,* 1995, pp. 386–387.

Vinogradov, V.I., Rb–Sr and K–Ar Dating of Blue Clays in the Baltic Region: Implications for Geology, *Stratigrafiya. Geol. Korrelyatsiya*, 1997, vol. 5, no. 6, pp. 111–116.

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